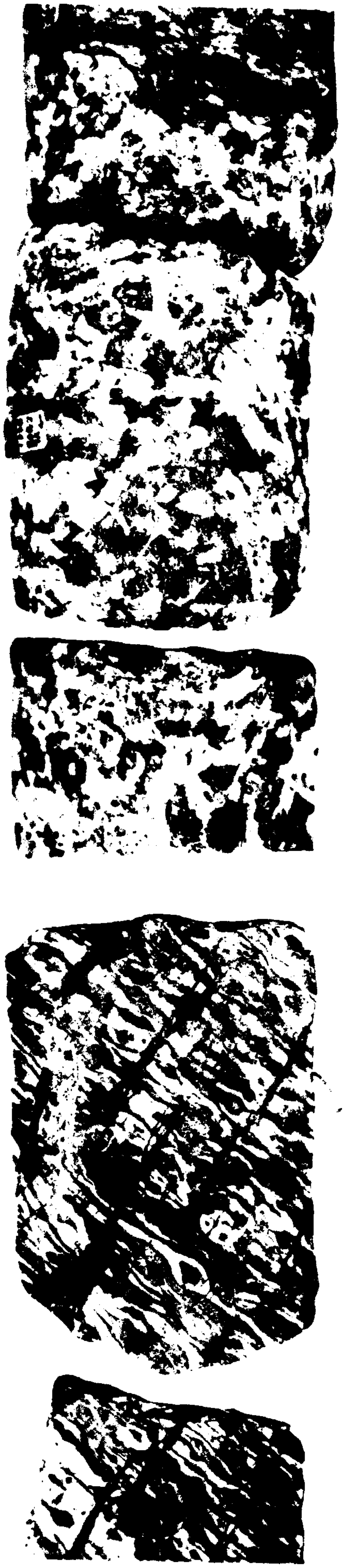

WHOI-89-39

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JOI/USSAC Workshop Report

Drilling
The Oceanic Lower Crust and Mantle

A Global Strategy for Exploring
the Deep Oceanic Crust and Mantle in the 1990's

Cosponsored by the WM Keck Geodynamics Program
and the International Lithosphere Project

March 7 - 10, 1989

Woods Hole, Massachusetts

COVER PLATES

On the cover and inside covers of this report are a selection of photographs of rock drilled from Hole 735B in the Indian Ocean. The hole was drilled on a wave cut platform at the crest of a major ridge flanking the Atlantis II Fracture Zone. This platform was an emergent island formed near the ridge-fracture zone intersection some 11 million years ago by faulting and uplift of rock some 3 km from the rift valley of the SW Indian Ridge. Subsequently the island was cut down below sea level by wave action and then subsided some 700 m as sea floor spreading moved it away from the active ocean ridge. It exposes rocks from the deepest layer of the ocean crust consisting of gabbros formed in a magma chamber beneath the floor of the ancestral rift valley. With the 2 km tough brittle carapace of basalt and diabase comprising layer 2 of the ocean crust stripped away by faulting and erosion, the platform presented the opportunity to directly sample the lower ocean crust without first drilling through layer 2: a technical feat yet to be accomplished in the 20 year history of scientific ocean drilling.

The 500 meter section drilled was a continuous undisrupted section of the lowest layer of the ocean crust and provides the first direct look at processes occurring beneath a mid ocean ridge which form two thirds of the ocean crust.

COVER

Top: 15 cm long section of coarse grained olivine gabbro displaying characteristic equigranular subophitic texture of the most common rock type drilled (over 300 m). Nearly free of alteration and undeformed, the sample is typical of material that can be studied to understand crystallization of magmas in the deep crust.

Bottom: Oxide-olivine gabbro gneiss formed by ductile deformation and shearing during extension and lithospheric necking below the rift valley floor during rift valley formation. Ductile deformation zones occur locally throughout the core and extend from syn to post magmatic deformation as the crust formed and cooled even as it was extended. Black veins formed orthogonal to the foliation are amphibole filled and are typical of the principle alteration phase found in the core. Low temperature greenschist facies alteration is conspicuously absent.

INSIDE COVER

Top: Foliated oxide olivine gabbro cut by a late undeformed trondjhemite illustrating the syn-magmatic character of deep crustal deformation.

Bottom: Hydrothermal breccia zone with rotated fragments of gabbro in a matrix of hydrothermal plagioclase representing a high temperature upflow zone, providing a first look at the deep plumbing of seawater circulation in the ocean crust.

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The Workshop on Drilling the Oceanic Lower Crust and Mantle and publication of this report was funded by Joint Oceanographic Institutions (JOI Inc.) and U.S. Science Advisory Committee (USSAC) award JPO-499 provided to the Woods Hole Oceanographic Institution, and through support provided by the W. M. Keck Geodynamics Program of the Woods Hole Oceanographic Institution.

Approved for distribution: ______________________

David A. Ross, Chairman
Department of Geology and Geophysics

When citing this report, it should be referenced as: Woods Hole Oceanographic Institution Technical Report WHOI-89-39.

JOI/USSAC Workshop

Drilling the Oceanic Lower Crust and Mantle

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JOI/USSAC Workshop

Drilling the Oceanic Lower Crust and Mantle

Cosponsored by the WM Keck Geodynamics Program
and the International Lithosphere Project

Foreword

Henry J.B. Dick, Convenor

This workshop was convened to follow up on the Second Conference on Scientific Ocean Drilling (COSOD II) to devise a specific plan for deep crustal and mantle drilling over the next decade. Since COSOD II, however, there have been several developments which have had major impact on planning for this drilling. These include new and evolving models for volcanic segmentation at ocean ridges, a growing appreciation that faulting and deformation are an integral feature of the ocean crust, and the recent successful drilling during Ocean Drilling Project Leg 118 into a tectonically exposed section of layer 3 at Site 735B at the Atlantis II Fracture Zone in the Indian Ocean.

Site 735B demonstrated that layer 3 can be drilled with presently available technology with very high recovery rates: an experience quite unlike the discouraging attempts to drill the hard brittle fractured basalt and diabase of layer 2, where drilling rates, hole conditions and recovery of rock is frequently poor. This success dramatically increased the scientific community's enthusiasm for deep crustal and shallow mantle drilling, as it now appears that drilling this heretofore unexplored region of the earth promises great scientific rewards. The presence of long cores from layer 3 for inspection at the workshop, the first ever sampled *in-situ*, wondrously focused the minds of the attending scientists on the possible returns of a systematic drilling program targeting deep crustal and shallow mantle rocks. It is key that, despite the unroofing, and shallow level emplacement of the crustal block drilled at Site 735B, the rocks drilled preserve a virtually intact section of layer 3. The nearly continuous core records igneous intrusion, high temperature hydrothermal circulation, lithospheric necking and brittle-ductile deformation beneath the median valley of the SW Indian Ridge 11.5 million years ago. The section is largely free of late low-temperature alteration, deformation and tectonic disruption present in plutonic rocks dredged from bounding fault scarps on similar large tectonic blocks adjacent to fracture zones. This demonstrates a largely unsuspected potential for using tectonic exposures of plutonic rocks, common in the world's oceans, to drill and study **undisrupted** sections of the deep crust and mantle.

Equally important in planning for future drilling is the growing appreciation of the complexity of the internal structure of the ocean crust - both igneous and tectonic. In part, this is the result of the new segmentation models for the architecture of crust formed at ocean ridges (Francheteau and Ballard 1982, Whitehead et al. 1984, Crane 1985, Schouten et al. 1985, Macdonald 1987, Dick 1989). These models view an ocean ridge as comprising a series of shield volcanoes overlying regularly spaced magmatic centers which undergo continuous extension to form the ocean crust: predicting major lateral changes in its stratigraphy and composition from the central to the distal portions of a volcanic segment. In addition, although numerous proposals have stressed the importance of drilling a tectonically undisrupted section of the ocean crust (a section preserving an intact igneous stratigraphy, free of internal disruption and foreshortening due to faulting and extension), such a section is unlikely to exist. While the effects of the numerous transform faults cutting ocean ridges have long been recognized, or supposed, there is an increasing awareness of the inherent internal tectonic structure generated throughout the ocean crust by continuous lithospheric necking and brittle-ductile deformation at ocean ridges. While deformation, extension, and hydrothermal alteration are omnipresent at fast-spreading ridges, and always accompanying igneous activity, they are probably the only continuous processes operating beneath slow-spreading ridges. For understanding the fundamental nature of the ocean crust and its formation, deformation, faulting and alteration are as important as igneous processes. Far from being dismayed by the presence of faults and ductile deformation zones in sections of layer 3 and the mantle, they require attentive study as they are an inherent, integral and primary feature of the ocean lithosphere.

As a consequence of these developments, the community has come to realize that while obtaining complete penetration of the crust at a few sites remains a critical goal for ocean drilling, these will be inadequate to characterize a heterogeneous ocean crust. Thus, in order to evaluate fully crustal composition and structure, crustal drilling must include both an ongoing attempt to attain total crustal penetration, and a major program to drill offset partial sections of the deep layers of the crust and their critical contacts. Accordingly, this workshop has formulated a global strategy for using drilling to systematically study an ocean crust whose composition and structure is laterally variable and changes with spreading rate and tectonic setting.

JOI/USSAC Workshop

Drilling the Oceanic Lower Crust and Mantle

Cosponsored by the WM Keck Geodynamics Program
and the International Lithosphere Project

I.
Steering Committee Report

Introduction

In March 1989 154 scientists from 11 countries met for 3 days to assess the status of deep crustal and shallow mantle drilling in the oceans and to make specific recommendations for a comprehensive strategy for the study of the deep ocean crust and mantle over the next decade: a study which uniquely requires the capabilities of the *JOIDES Resolution* due to the inherent stratigraphic nature of the problem of understanding the formation of the lower ocean crust and mantle.

A major impetus for this workshop is that without ocean drilling, it is unlikely that the scientific community will ever be able to determine the average composition of the ocean crust, or acquire a real understanding of its evolution to evaluate its potential economic and environmental importance. This is fundamental to understanding earth history and the formation of its continents and seas. Thus, the proposed program can well be compared in importance to the first sampling of the Lunar crust during the Apollo Program. Overall, the scientific impact of this program may be equal to obtaining and studying the moon rocks, though the cost will be orders of magnitude less.

The workshop met in general discussion sections for a day and a half and then broke into six separate working groups. The entire group reconvened several times for working group reports and general discussion of their conclusions. This report includes 6 separate reports written by the working groups and presents the specific objectives and strategies for deep crustal and shallow mantle drilling arrived at by each. The Steering Committee in turn, based on these reports and the general consensus determined from the meetings of the workshop as a whole, makes the following recommendations to the Ocean Drilling Program, JOI/USSAC, and to the National Science Foundation.

Major Recommendations

* **The highest short-term priority (5-10 years) is a systematic program of drilling offset partial sections of tectonically exposed deep crust and shallow mantle.** This is a significant revision of previous strategies for the study of the deep ocean crust and shallow mantle. Over the next decade of drilling, this program will require the largest portion of crustal drilling time. The offset sections program is a crucial part of the overall strategy for understanding the evolution of layer 3 and the shallow mantle, and a necessary complement to total penetrations of the ocean crust, as multiple penetrations of the layer 2-3 boundary and Moho are necessary in order to properly assess the anticipated lateral variability of layer 3 and the shallow mantle. The time table for this program should include drilling a two km hole in the lower portion of layer 3 through the Moho and into the mantle within 5 years as well as comprehensive drilling of the layer 2-3 boundary.
* **Total crustal penetration of an *in-situ* intact section of ocean crust remains the overall highest long term (10-15 years) priority for ocean drilling.** Given the technological problems in achieving this priority, however, it should be stretched out to a fifteen year period. The community specifically requests that engineering development for this purpose continue unabated throughout the next decade. The community recognizes, however, that the major scientific return from the total penetration program is not likely to occur until it has successfully penetrated the layer 2-3 boundary. A major goal of the program is that this be done within the next decade. For this reason, the steering committee recommends that drilling continue at Hole 504B as long as practical since it is believed to bottom within a few hundred meters of the layer 3 boundary. Should this hole have to be abandoned, it recommends locating a new site on older crust formed at the East Pacific Rise.
* **The JOIDES Planning Committee should immediately constitute a Deep Crustal and Shallow Mantle Working Group.** This working group should be charged with the following two major tasks:

1. To recommend where to drill composite sections of the deep ocean crust.

2. To make a recommendation for the best location for a total crustal penetration to be accomplished over the next 15 years of ocean drilling.

In order to make these recommendations the working group must accomplish the following tasks:

A. Make a preliminary evaluation of available opportunities for deep crustal drilling following up on the recommendations of this workshop.

B. In conjunction with the lithosphere and tectonics panels, solicit and evaluate proposals for specific drilling targets.

C. Bring together all available site survey information.

D. Recommend additional site surveys as needed.

E. Evaluate these site surveys.

F. Match drilling objectives to drilling opportunities to produce items 1 and 2 above.

* **A consensus of the community is that drilling partial offset sections be done in regions offering the maximum opportunity to drill nearly complete composite sections of the ocean crust.** Given the tectonic complexity of the regions where deep crustal rocks are exposed, it is crucial that they be subject to as complete study as possible in order to plan intelligently such drilling to make full use of the opportunities presented. The community specifically desires that it not be driven by the availability of limited site surveys to a single region by default. Given the importance of selecting the best possible site, at least four and preferably five different localities should be evaluated for partial offset section deep crustal drilling. These should include at least two major fracture zones in an area of geochemically "normal" ocean crust (dominated by N-type mid-ocean ridge basalt) and one major fracture zone where the crust is geochemically heterogeneous. One or more non-transform exposures of deep crustal and shallow mantle rocks representing crust formed at both fast and slow-spreading ocean ridges should also be investigated.

* **The National Science Foundation and JOI/USSAC should convene a special committee to assess and make recommendations for post-cruise funding to meet the special needs for the study of long continuous cores of plutonic rocks.**

* **The JOIDES Planning Committee should convene a working group through the Samples and Information Handling Panel to recommend a new sampling policy more appropriate for the unique requirements for the study of plutonic rocks.**

A Global Strategy for Exploring the Ocean Crust and Mantle in the 90's

A consensus of the workshop and all the individual working groups is to obtain a total penetration of the entire oceanic crust and upper mantle in an area where this section is likely to be as complete as possible. This objective is consistent with priorities stated by COSOD I and COSOD II. However, the workshop participants recognize that it represents an exceedingly long-term objective. Recent drilling results, however, indicate that it is immediately possible to obtain a composite section of the ocean crust and determine its lateral variability by drilling offset sections in tectonically exposed deep crust. Given the recent segmentation theories for the structure of the ocean crust and evidence from ophiolites, it is clear that the ocean crust has a complex three dimensional structure, and could never be fully characterized by a few total penetrations. It is therefore necessary to explore its lateral variability through more expeditious methods. This can be done through drilling a series of offset holes through various parts of the section in a single area. In order to understand fully the processes involving the formation and lateral variability of the oceanic deep crust and mantle, it is necessary to investigate areas which include the range of tectonic variables present during lithospheric accretion. Any proposed program will necessarily be a compromise between a few total penetrations, offset holes in single areas and drilling in different areas with different spreading characteristics. We therefore recommend a drilling strategy encompassing both long-term and short-term objectives, as well as an attempt to address the variables involved in the accretion process. This strategy includes six categories of investigations as follows:

1. Progress on the complete crustal section (to the layer 2-3 boundary)
2. Drilling through the transition zones of the oceanic layers, most particularly the Moho
3. Obtaining long, uninterrupted sections of the plutonic part of the oceanic crust.
4. Obtaining a deep hole in the oceanic upper mantle
5. Drilling major fault zones
6. Transform zone drilling

1. Total Penetration of the Ocean Crust

The concept of obtaining a total penetration of the oceanic crust and upper mantle in one complete section has received continued support from the crustal drilling community since the inception of deep sea drilling. The conclusion of the COSOD II report makes it clear that the attainment of this objective must be considered an ultimate goal, with a projected target of somewhere into the next century. The workshop participants re-emphasize, however, that many of the objectives of the working groups can only be satisfactorily reached by pursuing this objective. To this end, we recommend that the concept not be abandoned, but rather that progress be made on deepening an existing hole or alternatively selecting and starting a new drilling site with more ideal characteristics. In any event it is essential that engineering improvements be made over this period in order to achieve a total crustal penetration within 15 years.

The short-term goal is to attempt to reach the boundary between oceanic layers 2 and 3 (into the gabbroic layer) within the presently conceived program (10 years). The site at which this objective is to be pursued should be one where the probability of deepening this hole further into layer 3 in a continuation of the drilling program is maximized. Potential sites for this effort include both existing open deep holes, and the alternative of selecting a new site(s) and beginning new drilling. Potential holes that might be deepened include 504B, 418A, 595 and 597. There are pros and cons to each of these sites, and they should be carefully reviewed by the proposed Deep Crustal Working Group. Alternatively it may be better to start anew at a site to be selected. We recommend that the Deep Crustal Working Group carefully evaluate the alternatives for reaching the Layer 2-3 boundary in the present program.

We note that a return to Hole 504B will occur shortly, and planning for a total penetration will be impacted by the success or failure of the attempt to clear and deepen this hole. In the event of failure at 504B, and should the Working Group favor the alternative of starting a new site, we recommend it be located in the Pacific, in crust formed at fast spreading rates. This is based on the expectation that crust formed at fast spreading rates will be more uniform than that formed at slow spreading rates, and thus a single hole is more likely to be representative of the total crustal section. In addition, tectonic exposures of deep plutonic rocks appear to be significantly less common at crust formed at faster spreading rates, which may make a total crustal penetration the only practical way to obtain samples of the deeper crust there. Furthermore, many of the other objectives for deep crustal drilling will be more easily obtained at slow-spreading ridges. Therefore the selection of a fast-spreading site for the first complete section will ensure an attempt to assess the variability in the accretion process with spreading rate. We recommend devoting 3 legs to reaching the layer 2-3 boundary as a start to the longer term objective of obtaining a complete crustal section.

2. Layer Transitions

A. Crust/Mantle Transition (Moho)

The longest sought objective of deep drilling in the oceans now appears to be readily obtainable through the strategy of drilling partial sections. A major objective of most of the working groups is to characterize the nature of the Mohorovicic seismic discontinuity, and to determine the petrologic transition from crust to the underlying residual mantle. The minimum requirements for this drilling would be to start in gabbro and drill through ultramafic cumulates into upper mantle lithologies. We expect that to characterize adequately the transition in one place will require holes of 1000-2000 m penetration. We envisage a 4 leg program devoted to this objective, divided into two phases, each of 2 legs. Following initial site selection, 2 legs would be devoted to drilling. Depending on the results of this drilling effort, the allotment of the next 2 legs could be decided. For example, if the objectives of the drilling are realized in the first two legs, a second site with contrasting geologic setting, e.g. different spreading rate, different magma supply characteristics, further from fracture zone, etc., would be selected for continued drilling. If the objectives are not reached following the first two legs of drilling, additional drilling time could be allotted to continuing the effort at the first site. *Drilling the crust-mantle transition is the highest short-term priority objective defined by this workshop.*

B. Layer 2 - Layer 3 Transition

In addition to the objective of reaching the layer 2-3 transition during drilling of a complete crustal section, the importance of characterizing variability of this transition was emphasized by several working groups. Therefore, this boundary should be drilled in several places in order to better define its magmatic, structural and hydrothermal character. An additional leg of drilling could penetrate and sample this transition zone in at least two places at slow-spreading crust, preferably in the same region selected for drilling the crust-mantle transition.

3. Long Sections of Layer 3

The ability to understand the processes involved in the generation of the oceanic crust, and the potential roles of magma chambers is critically dependent on obtaining long, uninterrupted sections of deep crustal layers. We recommend that 2 drilling legs be devoted to this problem, with a minimum objective of coring at least 2 sections, each about 1000 m long. The drilling of over 500 m of gabbro

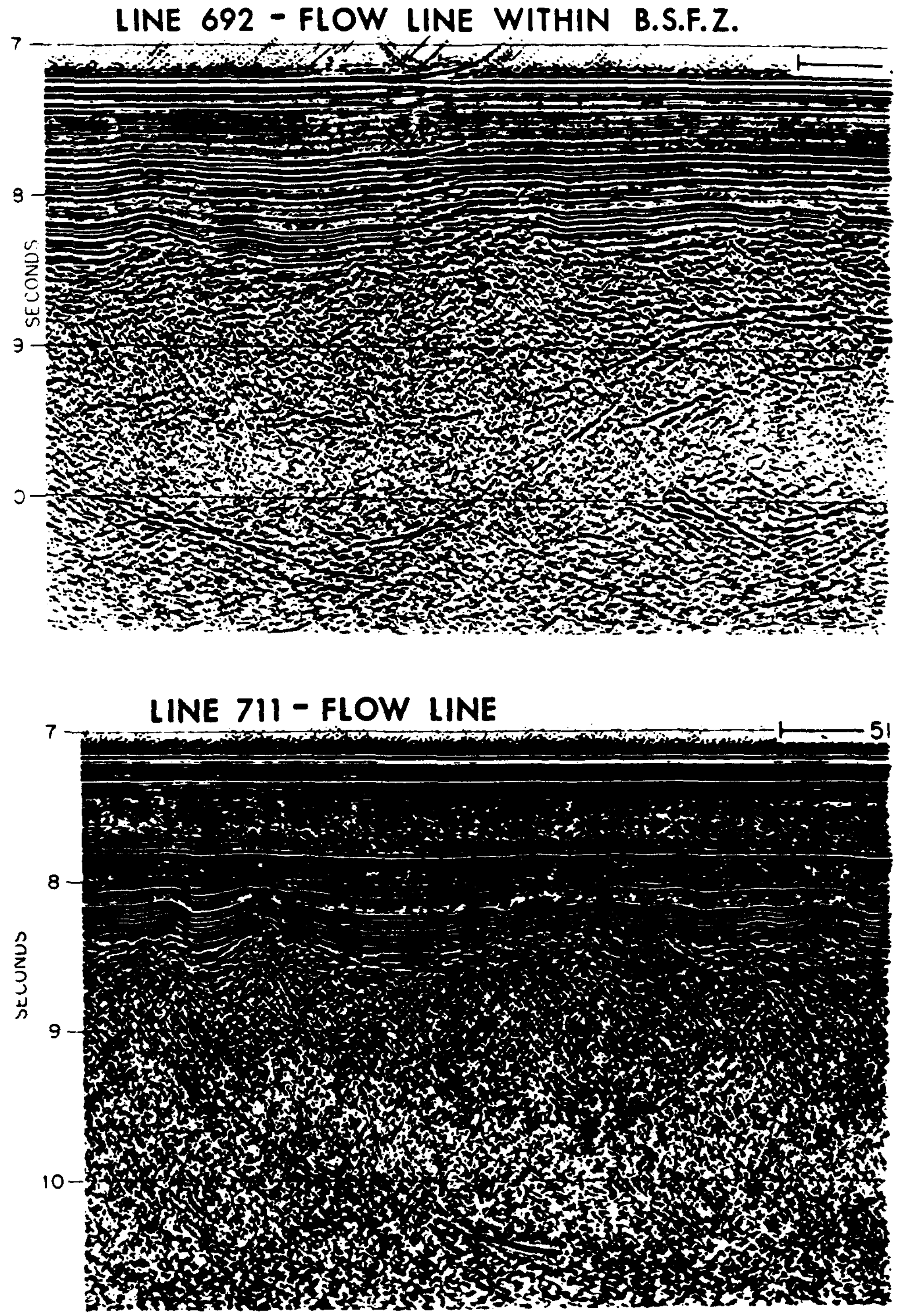

Fig. 1-1 Multi-channel seismic reflection profiles showing deep crustal reflectors imaged within Mesozoic ocean crust in the western North Atlantic south of Bermuda provided by J. Mutter, Lamont Doherty Geological Observatory. Profiles are roughly 18 km long.

in 17 days during Leg 118, indicates that this objective is not unrealistic. Ideally, the gabbro drilling will be located close to that for the crust mantle transition.

4. Mantle Deep Hole

Current hypotheses concerning the processes involving melt generation and melt extraction in the mantle suggest that these processes will impart vertical variations in extent of partial melting which in turn should result in regular vertical gradients in mineral chemical parameters and whole-rock geochemistry. In addition, analysis of dredge collections indicate that there is significant local modal petrographic and geochemical variability in the shallow mantle. Without stratigraphic relationships, it is extremely difficult to assess this "melting footprint" and interpret it in terms of melt formation and extraction processes. Moreover, more than any other studies of the oceanic lithosphere, the possibility of obtaining fresh mantle material for geochemical study is deemed extremely unlikely without drilling.

A deep hole into the oceanic upper mantle will allow investigations of the processes and test hypotheses relating to melt generation and extraction and will maximize the chances of recovering fresh material. If a suitable site can be found, (relatively shallow environment, yet unequivocally oceanic in nature) two legs of drilling should produce an adequate section into the upper mantle section (2-3 km). The Mantle Working Group stressed the importance of obtaining as deep a penetration as possible in a tectonically exposed mantle section, rather than multiple holes in contrasting settings. This hole would be complemented by the crust-mantle transition drilling to assess the lateral and sub-crustal variability of the shallow mantle section.

5. Fault Zone Drilling

It is generally acknowledged that plate separation at slow spreading rates must be associated with a large degree of amagmatic extension. In fact, a number of authors have recently conjectured that extreme extension along low-angle normal faults may be the mechanism by which lower crustal rocks are exhumed to the sea floor from their original level of emplacement (Dick et al. 1981, Karson et al. 1987), particularly in the proximity of ridge-transform intersections. Seismic images recently obtained in the ancient crust of the western North Atlantic have shown that the crust is pervaded by clearly defined reflecting planes dipping predominantly toward the old spreading center at about 30°. They are generally confined to the lower two-thirds of the crust though, significantly, some traverse the entire crust breaking the surface of the basement (Fig. 1-1). While magmatic layering within the plutonic section could explain some of the events, an attractive proposition is that they are faults caused by crustal extension. One surprising result, however, is that structures that traverse the whole crust are well imaged and much more common on isochron lines than on the flow line profiles. These structures are unlikely to be extensional in origin. They may result from thermal contraction or define a structural segmentation resulting from the mechanical response to extensional stresses, perhaps similar to those known from the East African Rift (Rosendahl 1987).

Motion along low-angle normal faults is at odds with known earthquake mechanisms of faulting at ridges (Toomey et al., 1988, for instance) and appeals to a deformational mechanism that has generated considerable controversy in studies of continental extension. The amount and nature of fault motion at ridges is often inferred from morphologic data or submersible observations. The cause of the reflectivity of the proposed faults observed in reflection images is not well understood.

Because tectonism and deformation are an integral part of the formation of the oceanic crust it is paramount that we improve our understanding of its nature. Many of the reflecting interfaces proposed to be faults are within reach of current technology drilling. A program of drilling focussed on assessing the role of faulting in the ocean crust should be part of any final strategy to explore it. Moreover, the master faults bounding the median valleys at slow-spreading ridges are the principal locus for the formation of sea floor topography and a fundamental expression of the oceanic rifting process. In order to investigate the relationships between amagmatic extension, vertical tectonics and hydrothermal circulation, we specifically recommend a leg be devoted to drilling faults near the margins of a slow-spreading ridge axial valley early in the program. Both headwall and footwall sections need to be recovered if possible.

6. Transform Zone Drilling

In the history of ocean drilling, a detailed program involving fracture zones has never been carried out despite the fact that close to a quarter of the ocean crust is formed in this environment. There are considerable uncertainties concerning the ability to successfully drill and recover core in fracture zone settings. Nevertheless, the problems involving the tectonics of fracture zones, the effects on hydrothermal circulation, and the evidence pertaining to the state of stress and rheology of lower crustal and mantle rocks in transform valleys is of paramount importance. Deep photogeologic studies of transforms indicate that there are significant exposures of deep crustal rocks located in these regions. Providing that a detailed photogeologic reconnaissance is available, the devotion of one leg to transform drilling will make an important contribution to understanding the state of stress, tectonic processes, and the nature of the crust occurring in transform valleys.

Summary Strategy

The above program is an attempt to encompass the principal objectives of the working group reports. This program will require approximately 14 drilling legs as shown below.

OBJECTIVE	LEGS
Total Penetration (Progress to Layer 2-3 boundary)	**3**
Layer Transitions	
Layer 2-3 Transition	**1**
Crust - Mantle Transition	**4**
Long Sections of Layer 3	**2**
Mantle Deep Hole	**2**
Rift Valley Master Faults	**1**
Transform Zones	**1**
TOTAL PROGRAM	**14 Legs**

Site Selection Criteria

1. Total Penetration Site Criteria

a. Water depth should be less than 4000 m to reduce the total length of drill string and the time required for drilling a 6 km thick section (i.e. a maximum of 10,000 m of pipe to reach the Moho). A major time consideration is the time required to change drill bits at the end of the drill string. "Round-tripping" the drill string can become the major limiting time factor for drilling.

b. Given the large number of legs of the drill ship required for this project, it is essential that the sites be located in a logistically reasonable region: one located within a reasonable distance of a major Atlantic or eastern Pacific port, with a wide weather window to permit drilling most of year.

c. Well defined and representative seismic structure (refraction and reflection). It is essential that the character of the site be determined precisely as representative of crust for a given spreading rate, such that the results of the drilling can be generalized with confidence for the region.

d. The tectonic environment must be clearly understood. The composition, thickness and internal structure of the ocean crust is now believed to depend on many different tectonic variables including: spreading rate, proximity to mantle hot-spots, magma supply rate, the absolute plate motion vector of the ridge at which the crust forms, proximity to fracture zones, and location within the volcanic segment where the crust originally formed. All these variables must be known with confidence.

e. Recognizing that formation of the ocean crust is an integral process of igneous and tectonic activity, nonetheless, it remains essential that the site is located in a precisely determined structural setting, with minimum tectonic disruption, away from unusual physiographic features.

2. Deepening Holes Of Opportunity

The choice of an existing hole for further drilling must first consider the likelihood of penetrating the Layer 2-3 boundary. For example, it would appear that Holes 504B and 418B would offer the best opportunity to reach this boundary with the smallest investment of drilling time.

3. Site Selection Criteria For Offset Partial Sections Drilling

There was a clear consensus at the Workshop that as many objectives be drilled as possible at a single location in order to achieve a composite section of the ocean crust. This creates fairly severe site selection criteria for the ideal drilling locale. This locale would have exposures of the Layer 2-3 boundary and Moho both along a lithospheric flow line from the mid-point of a volcanic segment (i.e. along the crest of a transverse ridge) and across the lithospheric flow line (i.e. on its wall) in order to address the three dimensional architecture of the ocean crust. The necessity for this is illustrated in Fig. 1-2, where a hypothetical cross section of a slow spreading ridge segment is shown. In this model the crust shows extreme lateral variations in composition from the mid-point of the ridge segment, where the input of magma from the mantle is believed concentrated, to its distal ends where largely stagnated and evolved melt crystallizes. Shown in Figure 1B and C are two hypothetical cross sections across a transverse ridge providing tectonic exposures of the plutonic levels of the crust. Section B is similar to the tectonic setting of Hole 735B, and presents the opportunity to drill a section of the deep ocean crust and Moho in crust formed at the mid-point of a volcanic segment. Section C is similar to the Vema Fracture Zone case described in a later section of this report. Here, drilling the basal cumulates and Moho could be done in a section of crust formed near the distal end of a spreading segment. Obviously, if the crust is laterally heterogeneous on the scale of a spreading segment, then the relative position of a drilled section of deep ocean crust is critical to its interpretation. Systematic dredging along transverse ridges has shown that these walls are not uniform, and that a variety of rock types can be exposed extending from mantle peridotite, through gabbro and

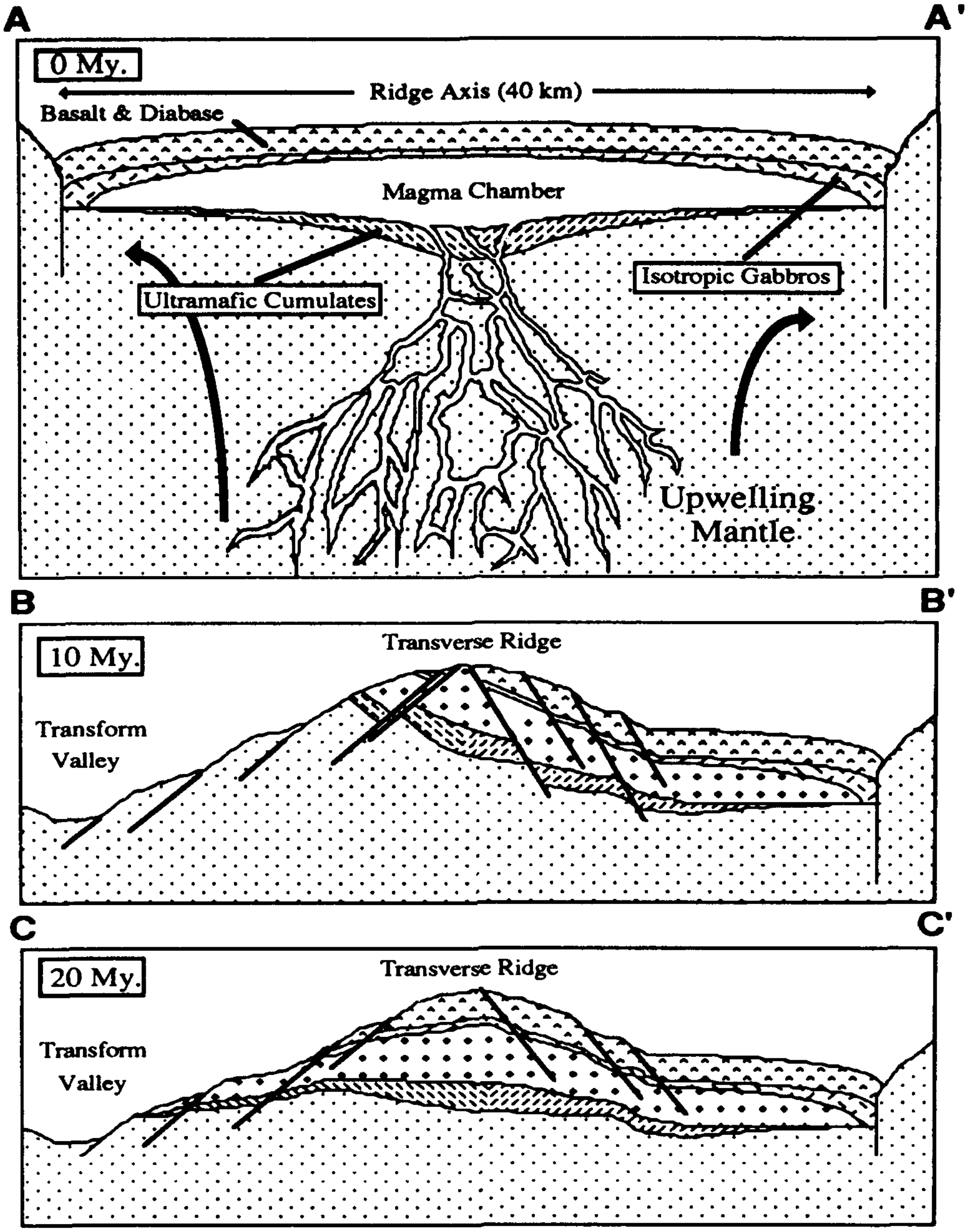

Fig. 1-2 Hypothetical sections of ocean crust generated at a ridge segment adjacent to a slow-slipping large offset transform fault all drawn parallel to the ridge axis. A: crust and upwelling mantle at zero age. B: cross-section after unroofing at the ridge-transfo. ı intersection and emplacement into a transverse ridge flanking a transform. C: cross-section of a different section of crust with less drastic initial unroofing. 'A' modified from T. Sisson (pers. comm.), 'B' and 'C' modified from Dick et al. (in prep.).

diabase to basalt along their crests. It is possible then that a transverse ridge, with the Moho and layer 2-3 boundary tectonically exposed both along the crest of the ridge and down its walls, can be found permitting a 3-D drilling program to explore the lateral heterogeneity of the crust.

Overall a preferred site for offset partial section drilling should have the following characteristics:

a. It should be possible to address multiple objectives in the same area to allow ultimate flexibility in achieving a composite section of the crust and upper mantle.

b. Exposures in the region should indicate that sections are appropriate for drilling objectives (i.e., drilling 2 km into the mantle, drilling the Petrologic Moho transition, drilling a 2 km plutonic section, drilling the Layer 2-3 boundary, drilling through master faults, drilling into a transform).

c. The regional plate tectonic setting must be well documented.

d. Seismic structure should be documented.

e. The region should be swath mapped and extensively sampled by rock dredge to provide a baseline for tectonic and geologic interpretation and extension of the drilling results to the regional scale.

f. Detailed photogeologic surveys dredging must be available for site selection, with local scale geologic maps prepared where possible.

g. Detailed sampling of drill sites by ROV or submersible and preliminary geochemical work should be completed on these and the regional scale dredge samples.

h. The site should be logistically feasible for multiple legs with little or no weather window and situated as close as possible to a major port with an international airport (e.g. Mauritius, Cape Town, the Azores, Lisbon, Boston, etc.).

Post Cruise Funding Requirements

The study of plutonic rocks presents a new challenge to the ocean community. On land where similar rocks are exposed in layered intrusions and alpine peridotites, their study has been found to be particularly time-consuming and difficult. A tremendous amount has been learned, however, about crustal and mantle evolution from these studies: information which can be gained in no other way. Compared to the study of oceanic basalts, the level of detailed study required to understand plutonic rocks is perhaps an order of magnitude greater. Thus, the issue of post-cruise funding for the study of these rocks was addressed both in the general sessions of this workshop and by the steering committee. A specific recommendation is made here that the NSF and JOI/USSAC convene a special committee to assess and make recommendations for the funding requirements for the study of plutonic rocks recovered by ocean drilling, and that the NSF make special provision for funding this work over the life of the drilling program.

Complete chemical and physical characterization of the core is essential. Correlation of the recovered core with down-hole logs will be necessary to identify the extent, and lithology, of missing sections. The core should be logged on a centimeter scale using as many thin sections as necessary to establish stratigraphic units on the basis of lithologies, structures and textures. A modal stratigraphy should be determined and appropriate sections identified for detailed studies. Initial work should involve non-destructive techniques, specifically microprobe/ion probe analysis to determine cryptic variations, mineral zonation, etc. The details of the mineral chemistry would be to a large extent dependent on the extent of lithologic heterogeneity.

Major, minor, trace element and isotopic analysis of representative samples (whole rock and mineral separates are essential to establish bulk rock composition, possible melt compositions and to constrain the extent to which the processes of recharge, mixing, fractionation and assimilation have been operative. These data are essential to constrain the geometry of magma chambers.

Stable isotopic and fluid inclusion studies are needed to constrain the sub-solidus processes that have affected the ocean crust.

Physical properties, e.g. density, Vp, Vs, thermal conductivity, electrical conductivity, permeability, and etc., should be determined on representative samples.

A rough estimate of the minimum funds required for the adequate physical and chemical characterization of the core is about 1.8 million dollars per kilometer of core. At a recovery of about 1 km/yr, this translates to 300 man years over the duration of a ten year program to study the evolution of oceanic layer 3 and the shallow mantle.

To put this requested funding level into perspective we point out that approximately 2000 man years of effort were expended on lunar samples during the active period of the Apollo missions, and that study of these samples continues to this day. In contrast perhaps 20 man years have been expended to date in the study of oceanic plutonic rocks which comprise two thirds of the oceanic crust and nearly a quarter of our planet's crust. It would seem reasonable that we expend at least a tenth of the effort put into the study of the lunar samples into the rocks from the first systematic sampling ever attempted of oceanic layer 3 and the earth's mantle.

II
Deep Drilling in the Ocean Crust and Upper Mantle Past Commitments, Present Prospects, Future Planning

James H. Natland & Steering Committee Members

"If we could first know where we are, and whither we are tending, we could better judge what to do, and how to do it."

A. Lincoln, 1858
Springfield Illinois

Introduction

Drilling igneous rock in the oceans has always taken time. Ambitious projects to drill holes thousands of meters into plutonic or ultramafic assemblages in the ocean crust will command a significant fraction of the resources of the Ocean Drilling Program, particularly the proportion devoted to deep ocean crust drilling. In order to devise a realistic plan for drilling the oceanic lower crust and upper mantle, accurate estimates of technological requirements and how long such drilling will take are essential. At this workshop, we wished to develop a program that was as consistent as possible with objectives stated in the COSOD I and COSOD II reports, but which recognized likely limitations on the time and the tools available to pursue it.

The Lithosphere Panel (LITHP) recently presented a *Long-Range Planning Document* (Oct. 1988), which basically endorses a formal recommendation of the COSOD II Working Group on Crust-Mantle Interactions concerning deep drilling. As stated on page 52 of the COSOD II report, this calls for coring a full and tectonically undisturbed section of ocean crust, from the top of the basalts to the mantle, in a single deep hole. This is to be preceded by drilling of three holes to depths of 2000-3000 m each by the year 1996, one of which would be selected to extend to the mantle by the year 2000. LITHP called for 10 drilling legs to accomplish this total program between the years 1992 and 2000. Eighteen additional legs were requested for other crustal drilling programs during the same period, including work at sedimented ridges, case studies in chemical geodynamics, and installation of long-term seismic observatories in holes at strategic locations in the ocean crust.

This chapter of our workshop report is an evaluation of this proposal, partly in light of the alternative strategy of drilling offset holes in tectonically exposed sections of deep crust and upper mantle. The feasibility of this alternative was shown by the successful coring of 500 m of gabbro, with 87% recovery and high coring rates, using a bare-rock guide base during ODP Leg 118. This had not been demonstrated at the time of COSOD II (July 1987), hence this workshop provides the first representative community assessment of the alternatives in light of the Leg 118 experience.

But even drilling of offset holes will require both time and persistence, and the question may still be asked whether an adequate effort can be mounted within the present framework of ocean drilling. That framework entails use of a single drilling platform (*JOIDES Resolution* for the foreseeable future) and a pluralistic planning structure serving a diverse international community of marine geoscientists. Assuredly, deep crustal drilling has received **the highest** thematic endorsements of both the COSOD I and COSOD II assemblies. But to be prudent, we must consider the possible impact of a major new initiative of drilling the deeper ocean crust and upper mantle on the drilling program as a whole, and within that the prospectus for all of crustal drilling outlined in Lithosphere Panel's *Long-Range Planning Document*. The technical aspects of deep drilling are no less important to evaluate, inasmuch as in the twenty year history of ocean drilling only a very few holes have ever exceeded 1500 m total penetration, and none has yet reached 2000 m in any setting, whether in totally sedimentary or igneous lithologies. With this background, hypothetical programs of two or more offset holes to such depths in bare-rock settings must be viewed as very ambitious.

The following sections first consider the present status of deep drilling into the ocean crust, then how long it will take to drill holes of 1000-6000 m total penetration into igneous rock at typical oceanic depths, based on technical estimates provided by the Ocean Drilling Program. Finally, the broader question of how such drilling can be accommodated in the overall drilling program is considered, and some recommendations are made.

Where Do We Stand?

Figure 2-1 provides a schematic history and prognosis of crustal drilling - whether undertaken (1968 to 1989), firmly planned (to 1992), or imagined (1993-2000) - for the combined Deep Sea

Drilling Project (DSDP) and Ocean Drilling Program (ODP). The horizontal axis gives the leg number and can be considered an approximate time coordinate based on the presumption that almost exactly six legs per year (of nominal 55-days duration port-to-port) have been drilled. Time has also been devoted to port stops, dry-docks, sea trials, engineering legs, and the like, and there was a numerical gap between Legs 96 and 101 (the DSDP-ODP transition), but six legs per year has been a very consistent average.

The histogram gives the number of legs within particular time periods that have been devoted to ocean-crust drilling. The definition of a crustal drilling leg can be somewhat ambiguous, but broadly speaking, any leg that has had, as a principal objective, the drilling or logging of ocean crust of any type, to assess its properties or composition, is here considered as a crustal drilling leg. Legs or portions of legs during which igneous basement was encountered in single-bit holes planned for other purposes are not included. Two short legs devoted exclusively to logging of ocean crust are counted as half-leg efforts, and half of a three-leg transect in the South Philippine Sea (Legs 58-60) which was jointly planned by the late Ocean Crust and Active Margin Panels, is counted as crustal drilling. A total of a half leg of crustal drilling is given to Legs 88 and 91 combined, during which two short penetration holes (<50 m. into basement) were drilled in order to emplace down-hole instruments for seismological studies.

The horizontal breakdown of the histogram is as follows. Legs 1-44 were the original National Sediment Coring Program of the Deep Sea Drilling Project, before international participation. Two legs, 34 and 37, were devoted to crustal drilling in this program. Leg 34 was not particularly successful, but Leg 37 succeeded in drilling a hole more than 500 m into basalt using a re-entry cone. This occasioned a major new initiative in ocean-crust drilling, commencing with the International Phase of Ocean Drilling (IPOD). Between 1975 and 1979 (Legs 45-70), more than a dozen ocean-crust drilling legs, and

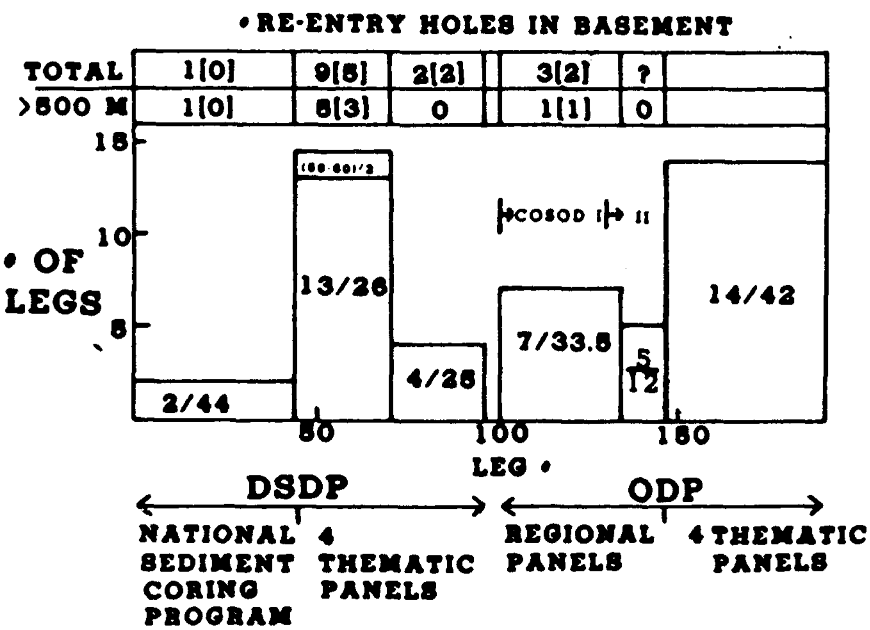

Fig. 2-1 A history and prognosis of crustal drilling. The columns give numbers of legs devoted to crustal drilling in five different portions of drilling history: 1) Legs 1-44, the National Sediment Coring Program; 2) Legs 45-70, a phase of DSDP/IPOD in which crustal drilling was formally emphasized; 3) Legs 71-96, a phase of DSDP/IPOD in which crustal drilling was de-emphasized; 4) ODP Legs 101-134, through the presently planned second year of western Pacific drilling; 5) ODP Legs 135-146, projected drilling in the Central and Eastern Pacific; 6) ODP Legs 147-188, projected to the year 2000 based on recent communications from the Planning Committee.

The lower portion of the diagram indicates the principal directions taken by the planning structure through time. The upper two rows of data indicate the number of re-entry holes into ocean crust attempted in (or planned for) each time interval, with the number of deep holes (>500 m. basement penetration) given in the next row. Row 2 is a subset of row 1. The number of re-entry holes still open is given in parentheses.

The timing of the first serious influence of the COSOD I and COSOD II reports on the drilling schedule is indicated in the middle of the figure.

the three legs in the South Philippine Sea, were undertaken, culminating in the drilling of Hole 504B to depths of more than 500 m into basement during Legs 69 and 70.

Of the remaining 26 legs of DSDP, only four were devoted to ocean-crust drilling. This change in drilling emphasis (beginning with Leg 71) was originally designed to allow assessment of the flurry of new results in ocean-crust drilling, and to exploit the newly designed hydraulic piston corer for paleo-environmental objectives. There was thus a formal decision to de-emphasize ocean-crust (and active-margin) drilling for a time, beginning with Leg 71.

At this writing, Legs 101-124 of ODP are completed, and scheduling is firm through the second year of western Pacific drilling (Leg 134). A total of 7 legs of crustal drilling have taken place during ODP or are scheduled to carry the program through 1990. Beyond 1990, plans are not yet firm, but are proceeding for 5 legs of crustal drilling in the Central and Eastern Pacific (CEPAC) program (here tentatively assigned 12 legs *in toto* based on the CEPAC prospectus). Beyond 1992, the number of legs to be assigned to crustal drilling is based on a preliminary response by Planning Committee (PCOM) to the Lithosphere Panel's *Long-Range Planning Document* (2 legs per year = 14 legs total in 1993-2000).

The upper portion of the diagram identifies the number of deep holes requiring multiple re-entries attempted in each time period through 1991 (and parenthetically, the number of these that are still open and can be re-occupied). All but two holes reaching at least 500 m into basement were started during the four years 1975-1979, and only one (Hole 735B, Southwest Indian Ridge) has been started since then. No other holes will be started with the expectation of reaching such depths through the end of the CEPAC drilling in 1992. At that time, fully half of the drilling program will have transpired (Legs 71-146) with only Hole 735B to mark a new initiative in deep crustal drilling, and three legs (1 still pending) deepening hole 504B to continue an old one.

Figure 2-2 breaks the proportion of crustal drilling during DSDP and ODP into percentages of the overall drilling program for each of the time periods shown. All legs are weighted equally except the several half-legs or shared programs outlined previously. The burst of crustal drilling between 1975 and 1979 amounted to more than half the total drilling program. The scale-back beginning with Leg 71 radically reduced the proportion of crustal drilling to less than 1 leg per year to the end of DSDP. A modest recovery ensued with ODP, and a somewhat higher proportion is expected for the CEPAC drilling period (and beyond).

Figure 2-2 can be read as both disquieting and encouraging. The disquieting aspect is the small percentage of time devoted to crustal drilling in the more recent past. Since 1979 (and projected through 1991), only 1.1 legs per year have been (or will be) dedicated crustal drilling legs. COSOD I, in 1981,

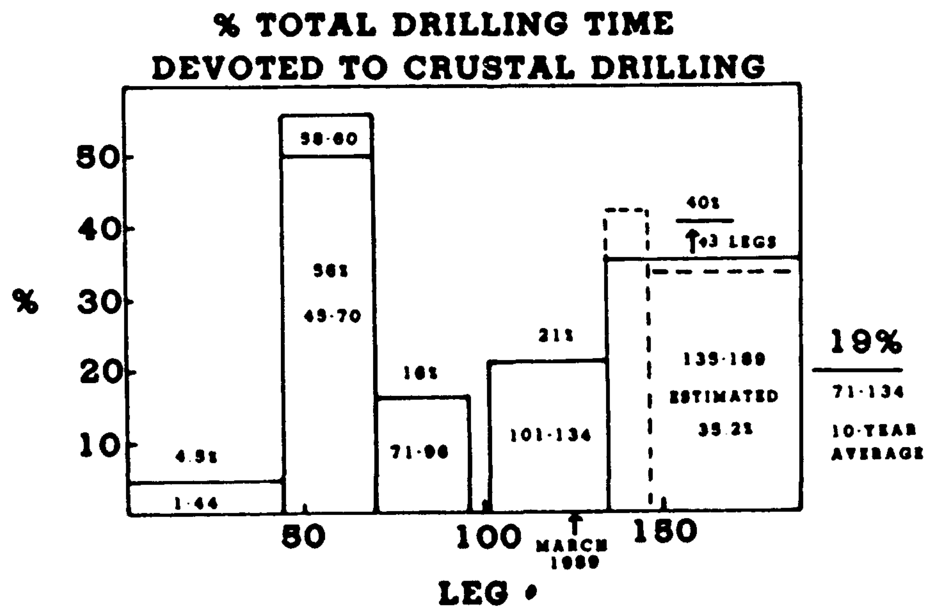

Fig. 2-2 The percentage of total drilling time devoted to crustal drilling, in the time periods presented in Fig. 2-1. The percentage over the last ten years is indicated on the right. Since Leg 45, when crustal drilling seriously commenced, the average (projected through Leg 134) is 31%.

advocated two principal objectives for ocean-crust drilling. These were 1) to reach the Layer 2-3 transition, and 2) to establish "natural" instrumented laboratories at an actively spreading ridge. We are very little closer to either of these objectives now than we were in 1981. In part, the lack of attention to these objectives can be viewed as consequences of the decision to circumnavigate the globe with the drilling vessel, and of the ascendancy of regional panels in the planning structure beginning in 1984. Indeed, many of the second-priority objectives identified for crustal drilling in the 1981 COSOD I report (e.g. hot-spots, oceanic plateaus, island arcs, back-arc basins) have been admirably addressed by the regional panels (Chagos-Laccadive Ridge, 90°E Ridge, Kerguelen, and old crust in the Indian Ocean; marginal-basins , back-arc spreading centers, and fore-arcs planned for the western Pacific; Ontong-Java and Loihi planned for the CEPAC drilling). But deep ocean-crust drilling of any kind has not been a significant factor in the overall program of ocean drilling since the end of 1979, and cannot be anticipated until at least 1993. Leg 118, during which Hole 735B was drilled near the Southwest Indian Ridge, was not a high-priority objective. It was viewed mainly as an attempt to drill into the transform domain of a fracture zone, and was scheduled for the Indian Ocean only *after* legs anticipated at an active margin and the Red Sea were cancelled. It was more strongly endorsed by the Tectonics Panel than LITHP. It is, in the entire history of drilling (142 legs projected to the end of 1992), the only leg to depart with the *intention* of drilling coherent sections of gabbroic or ultramafic rocks in the ocean basins (discounting attempts to drill serpentinite diapirs in a fore-arc on Leg 125).

The encouraging aspect of Figure 2-2 is that the community overall has been responsive to innovation, first in choosing to concentrate on crustal drilling after its feasibility was demonstrated during Leg 37, and then in emphasizing hydraulic piston coring when its advantages were understood following Legs 64 and 68. The bare-rock guide base and the mining-coring system are similar technological advances The guide base is a proven commodity. It allows targeting of any igneous outcrop with a reasonably flat surface, and may ultimately prove more useful in coring plutonic/ultramafic assemblages than fractured basalts at young ridges. Crustal drilling has been the impetus for both the guide base and the mining-coring system. We can hope that the financial investment for these will be followed by an increased commitment of time resources within the overall drilling program for crustal drilling.

Figure 2-3 gives the percentage of legs within the crustal drilling program alone actually devoted to, or planned for, deep holes utilizing re-entry cones and achieving at least 200 m penetration into basement. Logging mini-legs devoted to deep holes in the ocean crust are broken out separately in the histogram.

Historically, just about half of the total crustal drilling program has been devoted to deep holes, with the remainder dealing with objectives as disparate as hot spots, mantle geochemical heterogeneity, crustal

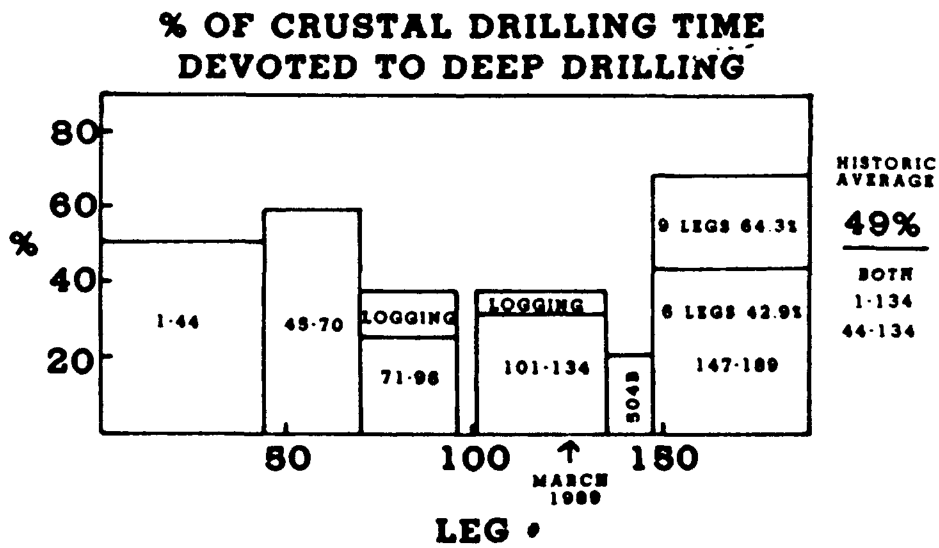

Fig. 2-3 The percentage of crustal drilling, as depicted in Fig. 2-1, devoted to deep crustal drilling (re-entries to more than 200 m penetration into basement), planned or projected through the history of drilling. Grand averages are given to the right of the figure. The right-hand column is hypothetical, but represents the period of time that can be influenced by Lithosphere Panel's Long Range Plan and this workshop.

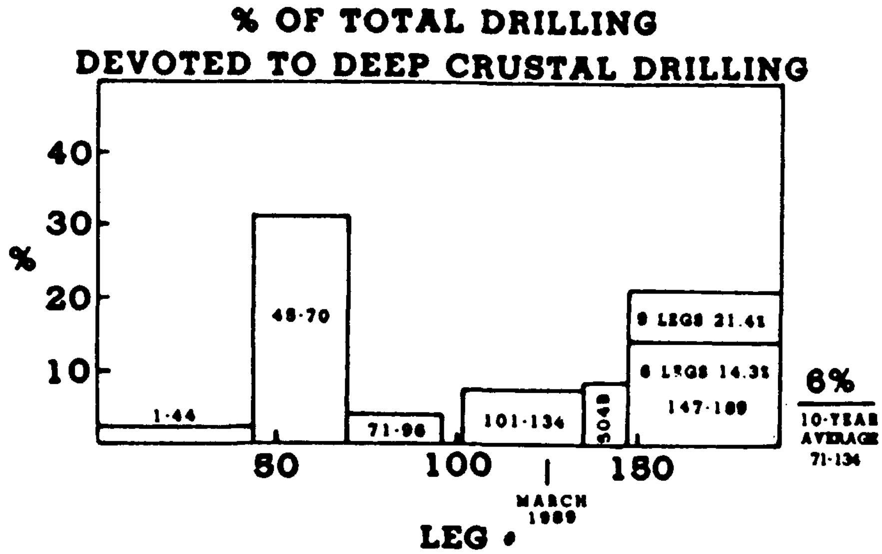

Fig. 2-4 The percentage of the total drilling program devoted to deep crustal drilling. The current ten-year average is given to the right, and the right hand column is again hypothetical.

aging, hydrogeology, arcs and back-arc basins, plateaus, newly rifted margins, and others. In the expected CEPAC program, however, only a single-leg return to Hole 504B is planned for deep crustal drilling (1 of 5 crustal-drilling legs, or 20% of the CEPAC crustal-drilling program).

The column on the right of Figure 2-3 is not based on firm plans, but simply shows the impact on an anticipated crustal drilling program of 14 legs (suggested by the Planning Committee) if either 6 or 9 legs are devoted to deep drilling, the subject of this workshop. Six legs will represent somewhat less than the historical average, and nine legs quite a bit more.

Table I
Deep Crustal Drilling
Legs 71-134

Deepen Hole 504B	700 m
Deepen Hole 462	130 m
Drill Hole 735B	500 m
Drill Leg 123	270 m
Total	1600 m

*Equals 133 m/year or 1 leg/2.9 years for deep crustal drilling

*Combined deep drilling and young ridges program (First priority COSOD I & II objectives) equals 1 Leg/2 years

Figure 2-4 gives the percentage of the total drilling program that has been devoted to deep crustal drilling during the several stages of its history. Notwithstanding the strong emphasis on deep crustal drilling in 1975-1979, the subsequent ten-year average of only 6% of the time resources of the program has resulted in little significant progress toward any of the principal COSOD I or II objectives in ocean-crust drilling. In graphic terms, deep drilling for basalts at any location for any purpose projected to the end of 1991 is progressing at an annual rate of 133 m/year; one leg has been devoted to these purposes every three years (Table 1). Combining deep-crustal drilling strictly to reach layer 3 or beyond (Leg 83 and 111 at Hole 504B and Leg 118 at Hole 735B) with work at young ridges (Legs 106 & 109), the commitment to the first priority COSOD I objectives in the ocean crust has totaled one leg every two years since 1979.

Obviously, these trends must be sharply reversed if drilling the deeper crust and upper mantle, and ocean-crust drilling overall, are to be successful. There *has* been a substantial commitment to developing engineering capability to carry out these tasks; lately engineering development legs have been scheduled. But thus far this has translated into little allocation of time for scientific exploration of the ocean crust. More significantly, since Leg 106, when the bare-rock guide base was first successfully used, virtually the entire emphasis of lithospheric drilling has centered on the push to develop the mining coring system for use in the eastern Pacific. As a result, a balanced crustal drilling program has not existed, initiatives for program development shifted to the regional panels, and opportunities for conventional crustal drilling in the Indian Ocean and western Pacific were not pursued for the sake of insuring engineering development and uncertain pay-off at the East Pacific Rise.

Time Estimates for Deep Ocean Crust Drilling

The Ocean Drilling Program provides a booklet giving estimates of average times required for basic drilling operations such as cutting cores, tripping pipe, scanning for re-entry, setting re-entry cones, wire line times for core retrieval, and the like. These estimates are used in detailed planning of prospective

Table 2
Parameters for Deep Drilling In 4500 Meters of Water

Penetration (m)	2500	3000	4000	5000	6000
Wire line Trip (hrs)	2.4	2.5	2.7	2.9	3.1
Trip String (hrs)	22.0	23.0	25.0	27.0	30.0
TV Scans for re-entry (hrs)	6.9	7.2	7.6	7.9	8.2
Re-entries (every 87.5 m)	29	34	46	57	69
Cores (9.5 m ea.)	263	316	421	526	632
Set-Up (sediment coring, setting re-entry cone)				5.3 days	
Coring Time (basalts)				2.5 m/hr	

sites for given legs, and can be extrapolated to depths anticipated for deep holes into the lower crust and upper mantle. Table 2 provides a breakdown of parameters used in computing time estimates for coring igneous rocks to various depths up to 6 km (a full penetration through crust of average thickness in the eastern Pacific). Table 3 sums the number of days required for each component of the drilling necessary to reach penetrations between 2500 m and 6000 m in 4500 m of water plus sediments. For each projected penetration in Table 3, provision is made for a minimal logging program, setting casing in the upper portions of especially deep holes, and set-up time (coring sediments; setting a re-entry cone). A 5% contingency is included (as is usual in planning a leg). Assuming 45 operating days per leg (plus 10 days transit), a full 6-km penetration in 4500 m of water requires 7.4 legs. A penetration to layer 3 (3000 m in most places) will require 3.3 legs. This assumes that no logging or down-hole experiments are done until the very end of drilling, that no pilot holes are drilled, and that drilling proceeds almost perfectly. Actual estimates based on experience in drilling deep holes suggests that 15% contingency is more appropriate (to accommodate early bit failures, jammed core barrels, fishing expeditions for lost equipment, etc.). Moreover, a full leg will certainly be necessary to accommodate all the logging and down-hole experiments that a hole to any of these depths will entail.

Figure 2-5 provides somewhat smoothed curves giving estimated times to drill deep holes in the ocean crust for various water depths (dashed projections to the ordinate). Nominal depth ranges of the Layer 2-3 transition, and the transition to the mantle, are shaded. The ranges of times required to reach these transitions for all water depths between 2.5 km (i.e. at an active ridge) and 6 km (ancient crust) are given by brackets in the upper portion of the figure. To reach the COSOD I objective of layer 3 from the top of pillow basalts will require 3-4 legs, using the assumptions embodied in Table 3 (no frills, minimal contingency and logging). Between 6.5 and 8.5 legs will be necessary to reach the mantle. Two curves for shallow, bare rock exposures at 700 m (e.g. Hole 735B) and 1500 m are shown. At Hole 735B, already 500 m deep, an additional 1500 m penetration could be achieved in a single leg (38 days coring, 4 days for re-entries, 5 days for logging, 8 days transit from and to Mauritius). Four offset bare-rock holes to 1200 m penetration apiece at depths between 3.5 and 5 km in the Vema Fracture Zone as advocated by one working group in this report, would require 5-6 legs.

Table 4 summarizes the time that will be required to accomplish the three-hole (one to mantle) plan outlined in Lithosphere Panel's *Long-Range Planning Document.* This stipulates that one hole be in thin crust near a fracture zone, and the other two in crust of normal thickness produced at both fast- and slow-spreading ridges. A bare minimum of 12.3 legs is required. Appropriate levels of logging (1 leg/deep hole = 2 more legs) plus contingency (15%, not 5% = another 1.2 legs), and a necessary feasibility leg for a target on the flank of the East Pacific Rise, push the likely commitment to nearly 18 legs. A program of 2-3 years, costing $90-135 million, will be required for ship-related activities alone.

Table 3
Time Estimates (days) for Deep Crustal Drilling In 4500 m Water plus Sediment

Penetration	2.5 km	3 km	4 km	5 km	6 km
Re-entry RT's	26.6	32.6	47.9	64.1	86.3
Re-entry TV Scans	8.3	10.2	14.6	18.8	23.6
Wire line	26.3	32.9	47.4	63.6	81.6
Coring Time	41.7	50.0	66.7	83.3	100.0
Logging	8.0	9.0	10.0	11.0	12.0
Casing			6.0	7.0	8.0
Set-Up	5.3	5.3	5.3	5.3	5.3
5% Contingency	5.8	7.2	9.9	12.7	15.8
Total Days	122.0	147.2	207.8	265.6	332.6
Total Legs (45 days operations)	**2.7**	**3.3**	**4.6**	**5.9**	**7.4**
Mining Hole to 1 Km	3.9	4.5	5.8	7.1	8.7

Where Can We Do This?

Site location is an important factor not just for computing how long it will take to penetrate the crust, but also in specifying important technological aspects of the drilling. Figure 2-6 shows a schematic cross-section of a spreading-ridge flank, with an idealized depth to the mantle of 6 km, and to the top of layer 3 of 2.7 km. Basement surface depths

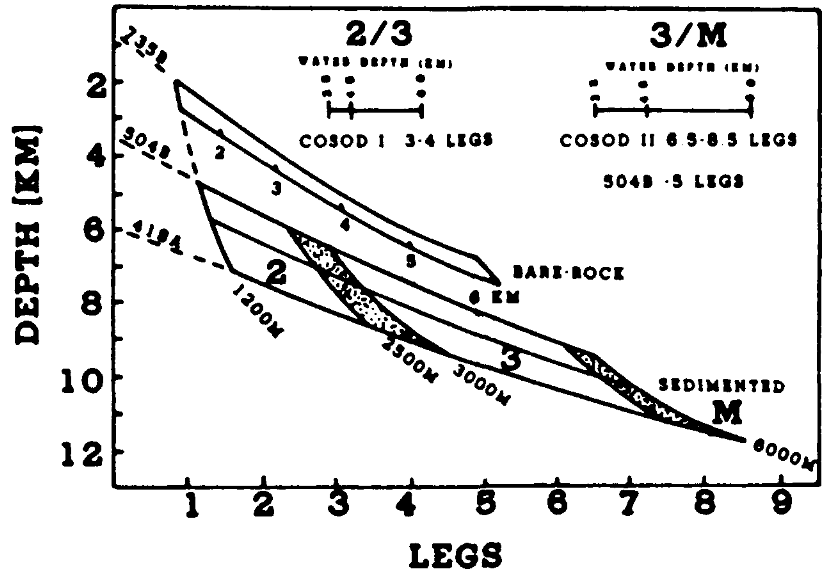

Fig. 2-5 Diagrammatic rendition of time estimates for deep crustal drilling, given in number of legs versus depth of penetration. The dashed lines give projections to depths of the top of basement on the ordinate. Depths of the Layer 2-3 and mantle transitions in typical Pacific crust are shaded. Curves for bare rock penetrations at uplifted blocks and transverse ridges are also given. The ranges of times in different water depths that the principal COSOD I objective (Layer 2-3 transition) and COSOD II objective (mantle) will take in full penetration holes, are shown in the insets.

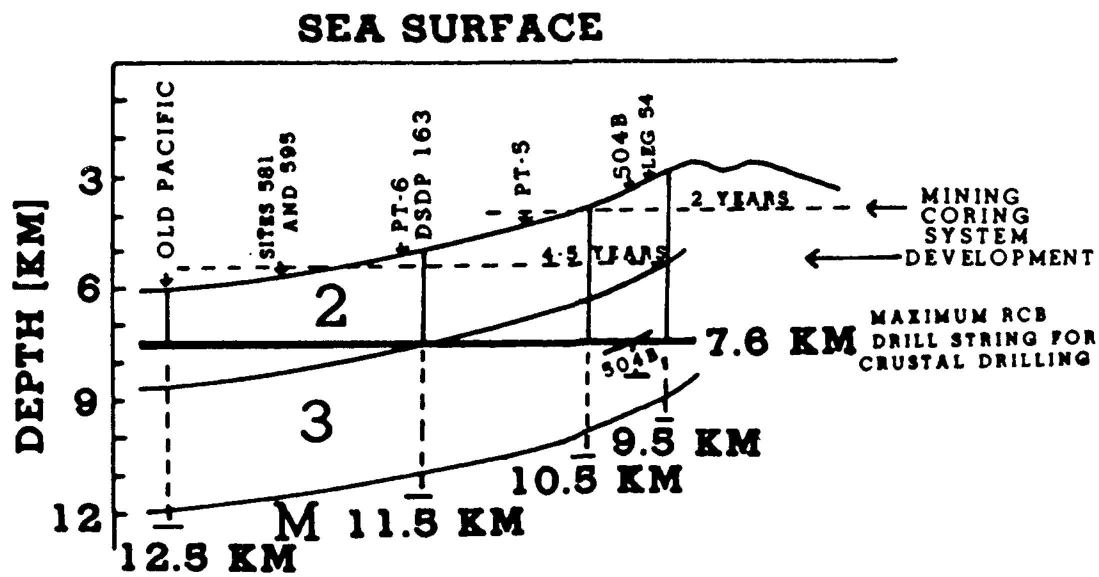

Fig. 2-6 Diagrammatic cross-section of a ridge flank, with nominal depths to the layer 2-3 and mantle transitions. The heavy horizontal line gives the present maximum drill strength for coring basalts. Solid vertical lines give the maximum penetration that can be achieved with this drill string in various water plus sediment depths. The drill string will have to be lengthened to depths specified below the dashed extensions of these lines if mantle is to be reached (and drilled for 500 m) at the particular water depths indicated. Only the thin crust at Hole 504B offers the possibility of reaching mantle with the present drill string. The projected limits to the mining coring drill string in 2 years and 4-5 years time are shown by the horizontal dashed lines. The figure illustrates the drilling time estimates in Table 3 for survey area PT-5, which is in 4500 m of water on Oligocene crust. PT-5 was originally planned as a backup to DSDP Leg 54 in 1977. Successful single-bit holes of 20-50 m at sites 163, 581, and 595 are placed schematically on the diagram to suggest options in the Pacific where we can consider drilling a deep hole.

range from about 2.8 km at zero age to 6 km in the oldest portions of the ocean basins.

The bold horizontal line at 7.6 km represents the present working limit of the drill string on *JOIDES Resolution* for coring basalt (9.1 km for sediment), based on information provided by ODP (G. Foss, pers. comm.). The vertical lines above 7.6 km give the portion of the crust that can be drilled with the present drill string in crust of different ages. The dashed extensions of these lines below 7.6 km indicate how much drill string must be added at each location to reach the mantle. This can be done off-the-shelf by adding heavier, stronger pipe at the top of the string, until the load limit of the present derrick is reached.

The present drill string is long enough to reach layer 3 in comparatively young crust, but not much more than half-way through it even at zero age. An exception is Hole 504B where the total crustal thickness is only 4 km. Conceivably, the mantle here could just be reached with the present drill string. If the present difficulties with the hole are resolved, and no others present themselves, this can be accomplished in another 3 legs. Even if a new hole has to be drilled from scratch, and assuming that no cores need be taken for 1.3 km (the present depth of Hole 504B into basalts), the mantle could be reached in 5-6 legs.

Table 4
Time Estimate
Lithosphere Panel Long Range Plan

	Legs
1. 2500 m mining hole (diamond coring system) in thin crust near a fracture zone	2.2
2. Two 2500 m rotary-cored holes at slow & fast spreading ridges (4500 m water depth)	5.6
3. Extend 1 rotary cored hole to the Mantle	4.5
Total	12.3
Add	
4. One logging Leg/hole	3.0
5. 10% more contingency time (15% total)	1.2
6. East Pacific Rise Feasibility Leg	1.0
7. Offset mining hole at one rotary-cored site to 1000 m	1.2
Grand Total	18.7

Elsewhere, but particularly on the flanks of the East Pacific Rise, holes in 4000-5000 m of water represent the best trade-off between drilling difficulty (experienced in young crust) and great water depths (characteristic of Mesozoic crust). A total drill string length of 11.5 km will be necessary to drill to the mantle in 4.5 km of water plus sediment. The new mining-coring system will not improve the likelihood of reaching the mantle, nor of proceeding at faster rates. Present plans suggest that mining holes up to 1000 m deep will be possible in crust at zero age in the comparatively near future, and up to 1000 m deep in 4500 m of water in perhaps 5 years time. These depths are also indicated in Fig. 2-6. But the anticipated greater coring rates are offset by the shorter bit life (requiring more frequent pipe trips), and the time it takes to set back and rig the special high-speed motor that turns the pipe. Moreover, mining coring holes will be narrower than those utilizing the conventional rotary-coring apparatus, and thus cannot be deepened by rotary coring without reaming. They will also require specially adapted narrow logging tools.

Thus, no matter what, truly deep holes well into layer 3 and potentially reaching the mantle will require conventional rotary coring from top to bottom, whether or not an offset mining hole is drilled in basalts (to improve recovery, for example). This stipulates almost certainly that such holes be targeted in reasonably old and altered crust, particularly in the eastern Pacific. This is why the time estimates in Tables 3 and 4 are based on a basement depth of 4500 m, corresponding to crust of Oligocene age in the Pacific.

Location of a target for these objectives in fast-spread crust is complicated by lack of certainty that such crust can be drilled anywhere. The two most recent attempts to drill into fast spread-crust (Leg 54 and Leg 92) showed only that atypical massive lava flows could be drilled in crust of Miocene and younger age; sheet flows and pillows were impossible. Core bits fail completely in a matter of hours in the highly fractured basalts on the flanks of the East Pacific Rise. Only two other short holes have been drilled into old crust produced at a fast-spreading ridge, at Sites 581 and 595, both for seismometer installations. Both were successful, as far as they went, but were in very deep water. And we still do not know if holes any deeper than this in such old crust will be successful. If the structure of fast-spread crust is to be ascertained with deep drilling, an exploratory leg in the eastern Pacific, to find where at intermediate depths (if at all) such crust can be drilled is essential, and should be conducted in the very near future.

What Else Will be Required?

Besides requiring a drill string at least 11.5 km long, a full crustal penetration to the mantle will necessitate other modifications to the ship and equipment. As explained by ODP engineer Steve Howard, modifications to the sand line (core-retrieval wire) will be needed, tapering it to achieve a total length of 11.5 km, and new, larger sand-line drums will have to be installed on the rig. Possibly, the derrick will have to be strengthened. Logging tools will have to be pressure-sealed to greater depths, and stronger coaxial cables devised.

Riser capability may not be necessary. ODP personnel see no particular difficulties in using down-the-pipe circulation to remove cuttings even from a hole 6 km deep, provided that the sides of the hole do not gradually give way, widening the annulus at some point. A more powerful pumping system may speed the process. They expect more difficulty in maintaining hole stability if the rocks are hot to begin with and fracture when suddenly flushed with cold water (as at Hole 504B), or if the hole provides a means for relieving stress.

A promising development is the use of sophisticated computerized sensors with the mining coring system. These monitor hole conditions and the status of core bits, allowing nearly instantaneous response to changes in drilling conditions, whether they are related to lithology or equipment. A system like this could be adapted to the rotary coring system, to improve its functioning and prevent equipment failure.

For the drilling to succeed, two other items are required. The re-entry cones and supporting casing should be designed to withstand 80-100 re-entries, and the casing below the cones must be reinforced to survive thousands of hours of pipe rotation (and frictional wear). Almost certainly, at least one option for casing off fractured basalts (to 1000-2000 m basement depth) should be anticipated. Below this, a narrower pipe some 4-5 km long will have to be used. This allows a longer drill string, and will reduce the likelihood of break-outs in structurally stressed deep rocks, but will restrict the dimensions of logging tools.

The surprising aspect of these modifications is that they seem comparatively modest, given the scale of the project. We have a proven drilling platform with exceptional station-keeping and heave-compensation capabilities. Re-entries are performed routinely and quickly. Deep holes have been drilled on land both with the rotary coring and mining-coring systems. The extremely smooth bore in the gabbros at Hole 735B (there wasn't a single major break-out in the hole despite clear evidence for sustained stress in the rocks) implies that two thirds of the ocean crust may be exceptionally easy to drill. Based on Hole 504B, the upper basaltic carapace is obviously not everywhere totally intractable. We are thus clearly on the verge of having the technical capability to drill a Mohole. The important questions now are 1) will such a hole be worth it scientifically? and 2) do we have the will and resources to do it?

How Will It Fit In?

Lithosphere Panel's *Long-Range Planning Document* calls for ten legs of drilling after 1992 to be devoted to deep crustal penetration, out of a larger program otherwise devoted to three principal categories of crustal drilling. These are 1) work at young sedimented or unsedimented ridges, to install "natural laboratories", monitor hydrology and seismicity, and resolve crustal structure in neovolcanic zones; 2) installation of a global array of seismometers in shallow holes, to improve understanding of the seismic structure of the planetary interior; and 3) well-designed "case-studies" devoted to problems in mantle heterogeneity, lithospheric recycling at subduction zones, and others. The overall program integrates recommendations from several of the COSOD II working groups, including those dealing with fluid-rock interactions, crust-mantle interactions, and tectonics. A summary of the long-range program is given in Table 5.

Table 5
Summary of Lithosphere Panel Long Range Plan*

	1989-'92 Requested	1989-'92 Planned	'93-'96	'97-'00	Post '92
Deep Holes	2	1	4	6	10
Young Ridges	4	3	4	4	8
Case Studies	1(Loihi)	1	2	4	6
Seismic Observ.	1	0	2	2	4
Total	8	5	12	16	**28**

Proposed:
Lithosphere Panel: 28 of 42 possible legs or 66.7%
Planning Committee: 14 of 42 possible legs or 33.3%
*As of October 1988

Beyond 1992 and until the year 2000, the plan involves 28 legs. In this period, there will only be 42 legs of nominal 55 day length, thus LITHP has asked for fully two-thirds of the total drilling program in its long-range document. The preliminary response from the Planning Committee has been to ask whether a sensible program can be devised on the basis of two legs per year, or 14 legs between the end of 1992 and the year 2000. Figure 2-7 shows how the different components of the projected drilling are proportioned, and the number of legs that might be devoted to each component if either 28 or 14 legs are scheduled. If plans proceed on their present course using the PCOM guidelines, deep crustal drilling will receive only 5 new legs of effort. This is clearly inadequate for the COSOD I objective of layer 3 at a single location.

For the sake of argument, suppose the decision is taken to dedicate 9 of the 14 legs to deep crustal drilling. The consequences for the remainder of the crustal drilling program would be dire. Little will be accomplished even on young ridges; the seismometer program and "case studies" would be reduced to the point where they would probably not be worth attempting.

The unequivocal rejoinder to PCOM must be that 14 legs are inadequate, and if crustal drilling is to be that restricted, then neither COSOD I or II primary objectives for crustal drilling can be seriously addressed.

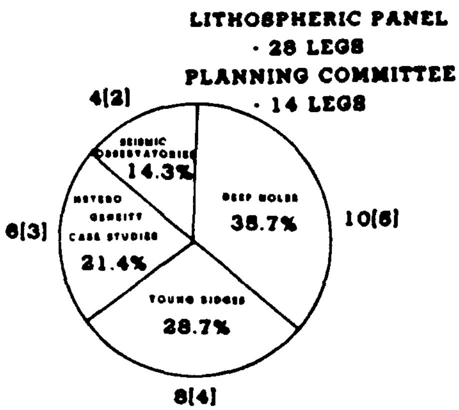

Fig. 2-7 The division of the crustal drilling pie suggested for the 28 Leg post 1992 program envisioned in LITHP's *Long-Range Planning Document*. Legs requested for each portion of the program are given outside the circle, and in parentheses the proportional number of legs implied by PCOM's 14 leg rejoinder.

A way out of the dilemma is to propose that the full program in the *Long-Range Planning Document*, or a modified version of it, be accomplished not by the year 2000, but, say, by the year 2005. Figure 2-8 presents a hypothetical division of effort based on a 72 leg scenario, with 32 legs devoted to crustal drilling of all sorts, carried to the end of 2005. A total of somewhat more than 44% of the total drilling program is devoted to crustal drilling. Within the 32 legs of crustal drilling (4 more than presently recommended by the long range plan), 14 legs are devoted to deep crustal drilling, as recommended by this workshop. This in turn is 4^% of the total crustal drilling program. The plan pro ides adequate attention to young ridges, but far reduced levels of attention to other programs, particularly "case studies", than was recommended by COSOD II. But even here, a sensible number of carefully designed programs can be considered. For more immediate planning purposes, between 1992 and 2000, a total of 18 legs are dedicated to crustal drilling, up by 4 from PCOM's suggestion of 14.

This is just one possible scenario, and the pie probably will end up being divided differently. But the clear implication is that crustal drilling has to receive a much more significant proportion of the time resources of the overall drilling program than it has, if the major thematic objectives enunciated repeatedly by the lithospheric community are to be achieved or even approached. The philosophies behind circumnavigation and regional panels were clearly inimical to those thematic objectives. The keys to convincing the wider community that the effort will be worthwhile are: 1. establishing that the scientific goals are unquestionably important and exciting, with broad based thematic content (pertinent to the interests of the Lithospheric, Tectonics, and new Rock-Fluids Panels); 2. demonstrating technical feasibility, particularly when that allows fresh approaches (i.e. Hole 735B); 3. providing a clear, precisely formulated plan for designing a drilling program and choosing targets; 4. maintaining flexibility in the light of technological advances or reverses; and 5. remaining realistic about the time and resources that will be required. This last was the principal drawback to the COSOD II recommendations.

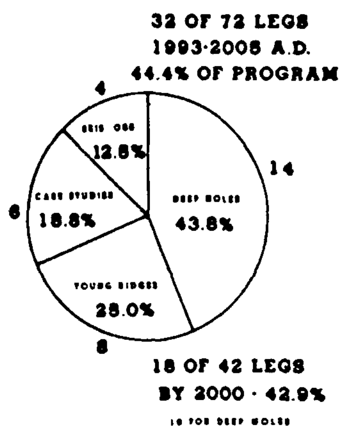

Fig. 2-8 A stretched-out drilling plan in which crustal drilling takes 32 out of 72 legs (44% of the total drilling program), projected between 1993 and 2005. Four additional legs are added to LITHP's long-range estimates for deep holes, based on recommendations of this workshop, bringing the proportion of deep drilling in the crustal program also to 44%. The rest of the program is retained as originally presented in the *Long-Range Planning Document*. This program model would entail 18 legs of crustal drilling by the year 2000, 10 of which would be dedicated to deep holes.

Conclusions and Recommendations

1. The 14 leg program for deep crustal drilling recommended by this workshop can take place, but must be designed within a larger program of crustal drilling that probably can only be accommodated in a twelve year period between 1993 and 2005. There will have to be a sizable shift in the emphasis of the total drilling program to include more crustal drilling, if 14 legs of deep crustal drilling are to occur.

2. Within this 14 leg program, the present Long-Range Plan for deep crustal drilling to reach the

mantle is only barely viable, using the most optimistic estimates. It will not be possible to accomplish anything else, and probably not even this.

3. An exception might be Hole 504B which, if salvaged, might be used to reach layer 3 in a single leg, and the mantle in three more legs. This would allow a substantial program of offset-hole drilling also to be accomplished.

4 The offset-hole drilling strategy, taking advantage of the bare-rock guide base, requires serious consideration as a means of directly coring plutonic and ultramafic rocks, learning whether such rocks can be cored for distances of 2000-3000 m, and exploring different tectonic environments in the ocean crust. Hole 735B offers the quickest test of truly deep drilling in rocks, since it can be penetrated to 2000 m in a single leg.

5. There is nevertheless a clear signal from the community (including many of the people present at this workshop) that the concept of a full crustal penetration should be pursued diligently, and that new targets in both slow and fast-spread settings need to be investigated.

6. A realistic interim goal (particularly if Hole 504B cannot be salvaged) therefore is the COSOD I objective of penetrating the crust to layer 3 at one new setting, which probably can be accommodated in a 14 leg program by the end of the year 2005, together with an effort in plutonic rocks in offset holes. Reaching layer 3 will set the stage for a later deepening to the mantle, which may then perhaps be planned under different assumptions (i.e. use of a separate platform).

7. In view of the strong interest expressed at this workshop in attempting a full penetration of crust produced at the East Pacific Rise, holes should be drilled on any or all of them. A proposal should be written for this as soon as possible.

8. We are close enough now to having the capability for a full crustal penetration that it is time for a serious study of this possibility. As part of the detailed planning for deep crustal drilling, we call for a full technical evaluation of drilling performance in deep holes attempted to date, involving a committee of scientists, engineers, and logging personnel, and supported by USSAC dollars for salary, travel, meetings, computer time, and publication costs. This committee would be commissioned to evaluate equipment performance and hole characteristics at different stages of drilling of deep holes, to investigate current and developing technologies that may be applied to future deep crustal drilling, and to prepare a report recommending how such drilling should be carried out, how and when new equipment and/or technologies should be phased in, and how much it will cost. The key to this recommendation is that scientists experienced in crustal drilling should strongly influence engineering development on the one hand, and guide program planning on the other. We have passed the stage when episodic attendance of guest ODP engineers at panel meetings is sufficient to guide the planning process.

WORKING GROUP REPORTS

III.
Mantle Working Group

Committee Members

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Introduction

The shallow oceanic mantle is the complementary residue of the generation of the ocean crust. As the principal component of the lithosphere, determining its composition and heterogeneity is critical in order to determine global fluxes in the earth. In addition, the shallow mantle preserves the integrated footprint of the melt generation process. Studying these rocks can lead to direct inference of the melting process unmasked by the numerous factors which modify the composition of ocean ridge basalts (e.g. magma mixing, crustal assimilation, fractional crystallization, post-cumulus wall rock processes, liquid immiscibility, etc.). Detailed study of the residual oceanic mantle, however, has been greatly limited by the lack of fresh samples and stratigraphic relationships: problems which can only be overcome by drilling long continuous sections of mantle rock below the sea floor weathering zone away from major faults which are known to localize hydrothermal circulation and serpentinization. The mantle working group defined the following principal problems (objectives) relating to the generation of the ocean lithosphere which we would like addressed through drilling:

1. What are the chemical, thermal and mechanical processes generating and extracting primary melt from the upper mantle (including the role of mantle metasomatism, and isotopic heterogeneity)?

2. What is the physical and chemical nature of the crust-mantle transition zone and the overall composition of the shallow mantle?

3. What are the physical properties that control the mechanical behavior of the shallow mantle? (What is the thermal structure? How is heat transferred? Where is the brittle-ductile transition and how does it vary with time?)

4. What is the correspondence between ophiolites and oceanic crust and mantle? Do ophiolites represent analogues or actual samples of the oceanic crust and upper mantle generated beneath major ocean ridges?

1. The chemical, thermal and mechanical processes of generating and extracting primary melt from the upper mantle.

A confluence of petrologic geochemical, experimental and geophysical evidence indicates that the magmas parental to mid-ocean ridge basalt are products of partial melting in the upper mantle. It has been established that the generation of the ocean lithosphere is the result of the upwelling of the asthenosphere between the diverging tectonic plates at the ocean ridges. This process is accompanied by decompression melting of the ascending mantle, with the melt migrating rapidly to the surface to form the crust, while the depleted mantle residue is emplaced immediately beneath it to form the crust-mantle boundary or Moho. As these complementary materials spread away from the ridges, they cool to form additional lithosphere. The critical details of this process, however, are virtually unconstrained by direct observational data. Without these it is difficult, if not impossible to know precisely how to evaluate the nature of primary magmas, the composition of the shallow lithosphere, or how to interpret the primary petrogenetic differences among dredged abyssal basalts. Dredged samples of mantle material are small, profoundly altered, and one sample can only be related to another by inference. Mantle xenoliths found in ocean island basalts similarly lack structural context and are likely to have been modified by non-ridge magmatic processes. While ophiolites provide excellent mantle exposures, they represent equivocal analogues to ridge-generated lithosphere, most have probably formed in an early rifting or supra-subduction zone environments, and their exact tectonic provenance ambiguous (i.e. spreading rate of formation, and proximity to hot spot, fracture zone or ridge discontinuity).

Study of dredged abyssal peridotites has provided important information about the extent of melting along mid-ocean ridges, particularly increased degrees of partial melting above mantle hot spots. This has been substantiated by subsequent studies of mid-ocean ridge basalts. The presence of residual melt has been documented in samples, but evidence, while tantalizing, is only fragmentary.

Mantle compositional heterogeneities are demonstrated by regional and local variations of isotopic and trace element abundances in mid-ocean ridge basalts and are also suggested by geochemical studies of ophiolitic peridotites. The existence and degree of heterogeneity in the shallow sub-oceanic mantle, and the extent of shallow level mantle metasomatism (alteration of the residual mantle by reaction with, or impregnation by, fluids ascending from below), however, is masked by the extensive alteration of sea floor samples and by their lack of stratigraphic context.

At present, unconstrained parameters are: (1) the depth interval(s) within which melts are generated and segregate beneath mid-ocean ridges; (2) the extent and variability of partial melting; (3) the compositions of melts both at the depth of generation and the point of delivery to the base of the crust; (4) the mode and rates of melt segregation, migration and entrapment in the mantle; (5) the potential interaction of mantle-derived melts and wall rocks. These processes are thought to be complex, and may result in long-lived mineralogic, elemental, and isotopic heterogeneities that range in scale from centimeters to kilometers.

Long, continuous cores of fresh oceanic peridotites will allow us to evaluate vertical variations in the extent of partial melting, using mineral chemical parameters and whole rock chemistry. Spatial variability of the mantle's composition can be addressed by analyzing multiple cores in the same region. The isotopic variability in the sub-oceanic upper mantle can likewise be evaluated. With continuous cores, we can establish a stratigraphy for the shallow upper mantle, and examine the mechanisms and the efficiency of magma extraction on a more informative scale.

2. The physical and chemical nature of the crust-mantle transition zone.

The nature of the crust-mantle boundary beneath the ocean floor and its correspondence to the geophysical Moho boundary remains enigmatic. The lithology and structure of the transitional zone are unknown. Present interpretations are based largely on ophiolite models and comparisons of physical properties of gabbros, peridotites serpentinites etc. with seismic velocities in the lithosphere. However, it is unknown whether the Moho is of magmatic, metamorphic or tectonic origin, or all of these. The crust-mantle transition is important for resolving petrologic and geophysical problems. Some petrologists feel that this transition may provide key information concerning the composition of primary mid-ocean ridge magmas. It remains to be determined why the Moho is well defined in some places and seismically transparent in others. By drilling through the lower crust into the shallow upper mantle in several places, we will establish the true compositional, mineralogical and physical nature of a fundamental seismic boundary.

3. The physical properties that control the mechanical behavior of the shallow mantle.

Laboratory measurements of common physical properties such as bulk seismic velocities, rock permeability, thermal conduction, and bulk density have been made only for arbitrary fragments of mantle rock. No analysis of a systematically sampled section in a well documented oceanic setting has ever been made. Although the effects of mineral orientation, rock fabric and microstructures upon these properties have been examined in ophiolites, it is not known what these characteristics will be like and how they will vary along ocean ridge segments formed at known spreading rates and physical settings.

Using laboratory measurements and down-hole logging, we can begin to model the thermal structure of the upper mantle and the processes whereby heat is transferred through the upper mantle into the crust. Such fundamental properties as the density and seismic velocity can be determined. Seismic anisotropy in the mantle could be determined directly by *in-situ* measurements, and related to mineral orientations, rock fabrics, and the distribution and orientation of micro-fractures. The brittle-ductile transition in the lithosphere is an important boundary on a global scale. Deep drilling in young oceanic lithosphere may provide us with a unique opportunity to examine the physical nature of this boundary. Certain geophysical signals are commonly attributed to several different types of sources. For example, the seismic velocity is a function of rock density, micro-structure, shear modulus etc. It is difficult to design independent geophysical experiments to solve the problem of ambiguity. By direct study of samples from drill cores, we can eliminate many hypotheses.

4. The correspondence between ophiolites and oceanic crust and mantle.

The study of ophiolites as analogues to oceanic crust and upper mantle has allowed development of reasonable models by which seismic data for oceanic crust may be interpreted. These studies have allowed spatially limited observations in sea-floor rift zones, transforms, scarps and drill holes to be extrapolated. Furthermore, ophiolitic peridotites provide the fundamental relationships from which the structure and composition of the oceanic mantle is inferred. However, it has become clear that both ophiolites and oceanic lithosphere are complex and variable and many geologists and geophysicists now challenge the assertion that ophiolites are generated at mid-ocean spreading ridges. In addition, we are often concerned that the processes of ophiolite emplacement may cause chemical alteration and physical disruption which can be very misleading.

The evaluation of ophiolites as actual samples of ridge-generated lithosphere requires a more complete characterization of the latter. Long continuous cores will confirm those physical and chemical aspects of ophiolites that are representative of oceanic crust and refute those that are not. With this information, ophiolite studies can be directed more carefully, and the aspects of ophiolites that can be used confidently as analogues for oceanic crust can be identified.

Information Needed to Address these Problems

1. **Fresh Samples** - necessary for all of the primary objectives.

2. Petrologic and geochemical data including petrography, mineral chemistry, and major and trace element whole rock data to determine:
   - A. Extent and variability of melt extraction
   - B. Temperatures of equilibration
   - C. Variations in the extent of partial melting with depth
   - D. Crust-mantle boundary definition in transition zone.

3. Physical property measurements in the laboratory on recovered cores (permeability, thermal conductivity, rock fabric anisotropy, crystal orientations, micro-fractures, and geothermometry) are critical, as well as *in-situ* measurements by down-hole logging, particularly for Vp, Vs, and seismic anisotropy.

4. Multiple holes and long continuous cores to assess the vertical and lateral lithologic and cryptic chemical variations.

5. To understand the melt generation and migration process in the mantle we need to drill features related to melt extraction like dunite dikes and pods.

6. To understand the physical nature of the crust-mantle transition and the shallow mantle we need petrofabric studies on oriented samples.

7. Information is also needed from related geophysical and geologic studies; particularly seismic (MCS) data to define reflectors, and shallow "Pogo rock-drill" holes (see abstract of Johnson et al., *this volume*) to define the local geology and structure near deep holes so that the drilling results can be interpreted in a broader context and generalized.

Why Drill?

1. We need fresh rock!! Peridotites exposed on the sea floor have been found to be extensively weathered and altered to clay where they are not previously serpentinized. The study of ophiolites on land shows that the serpentinization process is structurally controlled and most intense around major fault and shear zones where fluids have been free to circulate during emplacement of the peridotites to shallow depths. Dredged oceanic peridotites are sampled on major faults which have disrupted the crust. Presumably fresher material would be found if peridotites were drilled away from major bounding faults within tectonic blocks. Similarly, while ophiolitic peridotites are frequently heavily weathered, this is generally surficial, with road cuts or drilling revealing fresh material a few meters to tens of meters below the surface. There is every reason to believe, then, that samples sufficiently fresh for the large range of required geochemical and geophysical analyses can be obtained by drilling.

2. The study of plutonic rocks is fundamentally stratigraphic. Their evolution cannot be properly addressed with either grab or dredged samples which contain no stratigraphic information. In order to assess the features related to melt migration and inherent heterogeneity we need to study features on a scale of centimeters to kilometers. We must have long continuous sections of the upper mantle and the crust-mantle transition. This is the only way to get samples in stratigraphic context as outcrops are only sporadically exposed through the pervasive sedimentary cover on the sea floor. Even where large outcrops exist, there is simply no physical means of obtaining a continuous sampling other than drilling. A series of isolated samples spaced up the surface of a manganese covered outcrop, are little better than dredge samples.

3. We must ground-truth geophysical inference by measuring mantle properties either *in-situ* by down-hole logging or on the recovered core itself.

4. Drilling pristine oceanic mantle is of great significance for resolving the origin and evolution of ocean island basalts. The wide spectrum of mantle xenoliths found in ocean island basalts reflects a range in the character of the pre-existing deep sub-oceanic lithosphere underlying ocean islands, as well as an array of processes associated with generation and infiltration of host-related alkaline magmas in and beneath oceanic plates. The study of directly sampled, pristine, shallow oceanic mantle away from ocean islands is the essential "first step" to isolating those processes associated with the origin and propagation of ocean island basalts as opposed to those related to the generation of magmas at ocean ridges as inferred from features in ocean island mantle xenoliths.

Strategy for Drilling

Devising a strategy to drill the mantle and crust-mantle transition, and to adequately characterize these in a relatively small number of drilling legs is a first order challenge. Fortunately, the strategy which we adopt overlaps in large part with those of the other working groups.

A primary consideration here is that the stratigraphy of the shallow mantle is likely to vary both vertically and laterally away from the midpoints of ocean ridge segments, as well as with spreading rate, proximity to hot spots and in response to major tectonic features such as ocean fracture zones. Fig. 1-2 (Steering Committee Report) shows a hypothetical cross-section of the ocean crust drawn along the axis of a volcanic segment. This section represents an extreme view of crust and mantle architecture at an ocean ridge, but clearly illustrates the major challenges in assessing the lateral variability of the ocean crust.

In the model on which Fig. 1-2 is based, some form of gravitational instability focuses the melt migrating out of the mantle to beneath the mid-point of the ridge segment. Thus, the effects of melt transport in the shallow mantle, such as the formation of dunite veins and dikes by melt-wall rock interaction (Dick 1976; Quick 1981, Nicolas and Prinzhofer 1983), are largely concentrated in the mantle beneath the mid-point of the segment. In contrast, relatively few such features may exist in the mantle far from the midpoint of the ridge segment. This would account for the scarcity of such dunites in dredge collections, since these come largely from oceanic fracture zones, and represent a preferential sampling of the shallow mantle away from the midpoint of a ridge segment (Dick, 1989). Further, mantle upwelling beneath the ridge axis may be highly three-dimensional, consisting of regularly spaced diapirs which could closely resemble a string of salt domes rising from a buoyant layer beneath a small continental rift. In this scenario, the partially molten mantle rising between the lithospheric plates is likened to the buoyant salt layer, while the ocean lithosphere plays the role of more viscous continental crust. With such a three dimensional flow, however, the mantle upwelling directly beneath the midpoint of a ridge segment is likely to remain hotter to shallower depths than that emplaced beneath the distal ends of the ridge segment. Thus, we might predict that the mantle beneath the midpoint of a ridge segment undergoes systematically higher degrees of melting than that emplaced beneath the distal end of the segment or beneath the floor of a major fracture zone. Michael and Bonatti (1985) have found a small systematic difference in the degree of melting of mantle peridotites dredged from fracture zones and those drilled in small tectonic slivers at sites situated well away from fracture zones. The drill samples located further from the fracture zones consistently appear to have undergone lower degrees of mantle melting. Thus we conclude that it is critical to drill mantle situated close to and far from the midpoint of a paleo-ridge segment.

A second consideration in drilling the mantle is that at slow-spreading ridges the concept of long periods of intermittent amagmatic extension between major magmatic pulses is gaining increasing credence. This suggests that those features in the shallow mantle which are attributed to melt-rock interaction during melt transport, should not be uniformly developed along a lithospheric flow line. Thus, it is important not only to sample the mantle across a lithospheric flow line, but along it as well.

A major interest to this working group is the nature of the basal cumulates formed by the earliest stages of crystallization of primary magmas at the base of the crust. This is crucial to assessing the degree to which magmas transported through the shallow mantle can be assumed to be in equilibrium with it. The composition of melt in equilibrium with the mantle at any depth is highly sensitive not only to mantle composition, but to the pressure and temperature of the mantle as well. Thus, a magma formed in the mantle at 10 kilobars pressure (30 Km) would be in gross disequilibrium with the same mantle residue at 2 kilobars (at the Moho). Drilling the dunite residues and the mantle wall rocks produced by the shallow melt transport process, due to the rather restricted mineralogy of dunites (olivine and spinel), yields critical but limited information on the composition of melts passing through the top of the mantle section.

As shown in Fig. 3-1, a predictable consequence of a focused flow of magma beneath the ridges, is that the hottest, most primitive magmas will be concentrated in the magma chamber beneath the mid-point of a ridge segment. It is likely, that magmas emplaced towards the distal ends of the chamber will be considerably more evolved than those crystallizing at its center. This is likely to produce a substantial difference in the nature of the basal cumulates produced at the mid-points and distal ends of a ridge magma chamber. Pallister and Hopson (1981) have reported exactly such variations in gabbros at the Oman ophiolite, which they attribute to the emplacement of evolved magmas to the distal ends of an ocean ridge magma chamber. Studies which compare gabbros dredged from fracture zones to those from rift mountains far from fracture zones suggest that the fracture zone gabbros are consistently more evolved (Whitehead et al. 1984; Bloomer, Natland, and Fisher 1989; Dick 1989; Meyer et al. 1989) and have cooled more rapidly (Meyer et al. 1989). **Thus, in order to assess the composition of the**

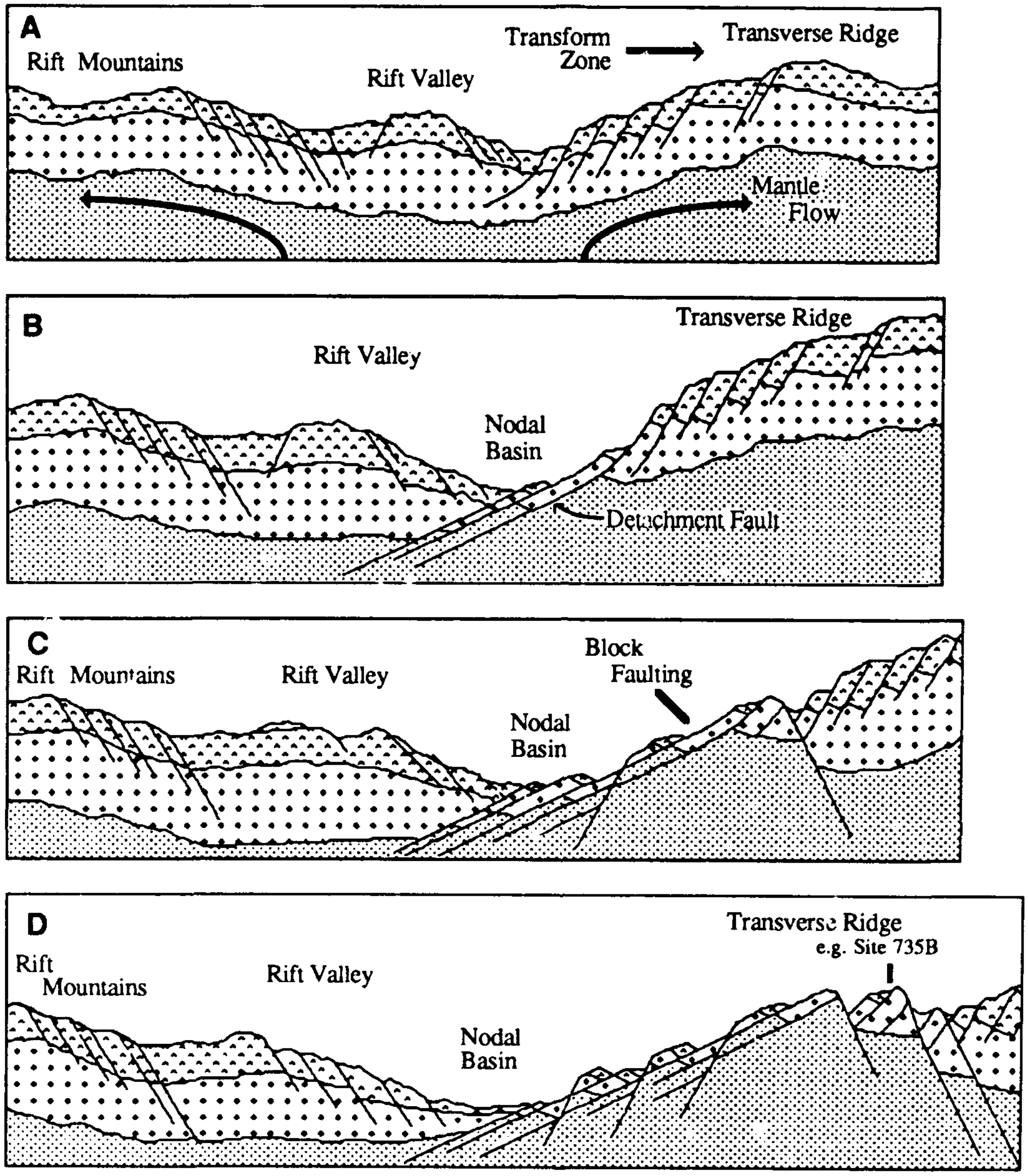

Fig. 3-1 Sequential temporal cross sections of a ridge near the ridge-transform intersection drawn across the rift valley parallel to the spreading direction and nearby transform based on the geology of the Kane and Atlantis II Fracture Zones (Dick and others, pers. comm.). Crust spreading to the right passes into the transform domain, while that moving left passes into the inactive extension of the fracture zone. A) Initial symmetric spreading, possibly at the end of a major magmatic pulse. B) Latter, the shallow crust is welded to the old cold lithosphere to which the ridge axis abuts, causing formation of a detachment fault, and nodal basin. C - D) Enhanced block uplift of the rift mountains at the ridge-transform corner forms a transverse ridge by regional isostatic compensation of the local negative mass anomaly at the nodal basin. Note that most of the basin lies out of the cross section plane, along the axis of the transform and fracture zone valley.

primary magma, and its relationship to the shallow mantle, it is critical to drill the Moho along a lithospheric flow line which can be clearly traced back to the mid-point of a volcanic center.

It is clearly important to drill mantle sections both along and across lithospheric flow lines. How this can be accomplished is illustrated in Fig. 3-1B and C. These show hypothetical sequential cross sections of a oceanic rift valley and a transverse ridge flanking a major transform fault. They are based on a model derived from dredging and detailed surveys of a large number of oceanic transforms and are highly generalized (Dick et al. 1987). A number of investigators have suggested that the walls of fracture zones expose a cross-section of the ocean crust (e.g. Bonatti and Honnorez 1976, Engel and Fisher 1975). Francheteau et al. (1976), however, have pointed out that the walls of fracture zones consist of a series of steep scarps and benches which appear to correspond to a series of up-stepping normal faults along which the ocean crust has been uplifted to form the wall of an active transform. None of these scarps appear to exceed a few hundred meters. As they correctly point out, none of these faults is capable of exposing a simple cross section of an ocean crust believed to be from 4 to 9 km thick. Dick et al. (1981, pers. comm.), however, suggest an alternate mechanism for exposing a crustal section on the walls of oceanic fracture zones. Noting that the apparent simple stratigraphy seen at many locations on fracture zone walls appears quite real, they suggest that a crustal weld periodically exists across ridge-transform intersections which causes the shallow levels of the ocean crust to preferentially spread away from the transform. In contrast, at depth, the hotter less viscous crust tends to spread symmetrically. This then creates the periodic formation of a long lived detachment fault which unroofs the deep layers of the ocean crust and shallow mantle (Fig. 3-1).

Low-angle detachment faults created by a crustal weld across the juxtaposed plates at a ridge-transform intersection would root most deeply at the plate boundary near the cold lithosphere of the older plate, and would shoal rapidly away from the plate boundary as the thermal effect of the old plate decreased. Thus, the faults would tend to expose the mantle and deeper crust most frequently near the floor of a transform. Shallower levels of the crustal section would be more frequently exposed further away from the fault as the brittle-ductile transition shoals away from the plate boundary. Since the transform walls uplift crust formed up to 20 km away from the plate boundary, it is not surprising that the unroofing of the crust by this transform edge effect produces a pseudo-stratigraphic cross section of the ocean crust from time to time, with mantle exposed near the base of the wall close to the plate boundary, gabbros at mid-depth, and basalts far from the transform at the crest of the transverse ridge where the effect of the crustal weld is more often negligible. It should be noted, as can be seen from Figure 1-2, that such **cross-sections are inclined**, not vertical, and that a section drilled high on the wall is only indirectly related to that drilled at its base.

Studies of transverse ridges show that the lithologies exposed at their crests vary substantially. While at 735B gabbros are exposed on the crest of the ridge, at St. Paul's Fracture Zone in the Atlantic, peridotites are emplaced to the sea surface at St. Paul's rocks. Detailed dredging along the transverse ridges, also shows that the exposures of peridotite and other plutonic rocks are limited with basalt, diabase, greenstone, gabbro and peridotite found at different sites on the crest of the same transverse ridge. This suggests that crustal pseudo-sections can also be found along the crests of such ridges as well as on their walls (Fig. 3-1D). Thus we propose that to drill the Moho from within layer 3 gabbros, a series of drill holes be situated as traverses along the crest and along the base of a transverse ridge, as well as down its walls. These holes should penetrate at least 500 m into the mantle. We prefer that, initially, such traverses be done at a single transverse ridge which exposes crust and mantle in a region where the basalts are of relatively uniform isotopic composition and represent the normal or N-Type MORB end-member. Time permitting a similar traverse or comparative sections should be done at transverse ridges which have formed in crust with different spreading rates and in geochemically heterogeneous crust near a mantle hot spot. We propose that 4 legs should be devoted to this Moho Drilling Program. This would permit drilling of approximately eight 700-1000 m sections through this boundary.

A high priority of this working group is to drill the longest possible section of the mantle at a single site. Since the shallowest mantle stratigraphy will be drilled during the Moho drilling program proposed above and as also proposed by the other working groups, we would prefer that this site be situated at a tectonic exposure of mantle peridotite in order to maximize the total section drilled. We seek at least a 2 km section of the mantle. Since the primary purpose of this site is to investigate the "footprint" of mantle melting, and since this footprint is likely to be best developed in the mantle directly beneath the midpoint of a ridge segment, the drill site should be situated on a documented lithospheric flow line from the center of a presently active volcanic segment. We propose 2 drilling legs devoted to this site, to be scheduled separately to allow preliminary assessment of the results of the first leg prior to continuing drilling.

Potential target areas

The proposed drilling program requires a three-dimensional exposure of the deep ocean crust and shallow mantle found for the most part at major slow-spreading ridge fracture zones. The program proposed here requires at least 3 major targets. In order of priority these are: 1) a site situated at a major fracture zone cross-cutting geochemically "normal" ocean crust, 2) a site situated in an area of geochemically heterogeneous ocean crust near a mantle plume, and 3) a site situated in "normal" ocean crust at a ridge whose spreading rate is different than that drilled initially. At present there are few clearly identified drilling targets. The final targets selected need to have exposures of the deep crust and shallow mantle on both the fracture zone walls and along the crest of the flanking transverse ridge. There are two sites which have been discussed extensively at this meeting which may meet these requirements:

1. The Atlantis II Fracture Zone, where good exposures of layer 3 have been identified and documented by drilling and TV survey, and where the Site Survey located gabbros and peridotites at many different localities and water depths. The principal disadvantage of this site is that it is situated far from major U.S. and European research institutions, and that the majority of earth scientists are less familiar with this ocean basin than the Atlantic and Pacific. Its principal advantages include that it is the only site where **we know** that we can successfully drill layer 3, and it has a remarkable shallow wave cut platform which has been scoured clean of manganese so that the exposed basement can be photo surveyed, sampled and mapped. This may be a unique situation and opportunity. The lack of familiarity of many scientists with this ridge system, however, does not reflect a lack of scientific information available, and it is generally well surveyed and sampled. Excellent magnetics, gravity and Seabeam surveys exist for the Atlantis II Fracture Zone. Photo geologic or video surveys and detailed sampling need to be done. The site is also logistically good as it is located only 2.5 days south of a major, centrally located, Indian Ocean port - Mauritius, and is only 7 days transit time from Cape Town a principal port for South Atlantic operations.

2. The Vema Fracture Zone is situated in the central Atlantic, and there exists a wealth of potential site survey information. The major disadvantage of this site is the lack of documented exposures of deep crustal and mantle rocks along the crest of the transverse ridge. If the crest of the ridge is covered with a limestone cap so that the basement geology can't be mapped, this would severely reduce the usefulness of this site. The major advantages of this site include its somewhat closer geographic proximity to major U.S. and European research institutions, the greater familiarity of most earth scientists with the Atlantic ocean basin, and the documented existence of pseudo crustal sections on its walls through a number of different submersible programs. Detailed photogeologic and sampling surveys are also needed here. Logistically, with the exception of the need to bring the ship back into the Indian Ocean for the latter, it is little different from the Atlantis II F.Z.

A number of potential drill sites for a mantle heterogeneity leg(s) also exist. 1) In the south Atlantic, the Islas Orcadas Fracture Zone exposes a major mantle section in an area with the greatest geochemical crustal heterogeneity yet documented. However, if you get seasick, you might not appreciate drilling at this latitude. Site information is also minimal. 2) The 15°20' fracture zone is well surveyed by the Russians, will shortly have a major submersible program on it, and is the location of a major geochemical anomaly. It also is situated in calmer seas. 3) The Oceanographer Fracture Zone is situated close to the Azores Hot Spot and there is a good deal of excellent survey data available. It is not known, however, whether there are good sites high on its walls. 4) The Kurchatov Fracture Zone is a very short offset cutting the crest of the Azores Hot Spot and the Russians have dredged mantle peridotites there suggesting that a suitable site might be found there.

Site survey requirements

The sites selected for drilling should all be in the context of detailed regional and local scale surveys and sampling. These requirements are discussed extensively by some of the other Working Groups, and we will avoid repetition here. One requirement that is essential, however, is detailed local scale geologic mapping and sampling. We note the traditional difficulty of sampling massive plutonic rocks by dredging and the ambiguity of location (± 500 m), and stress the importance of *in-situ* sampling at the local scale. We would like to emphasize the usefulness of developing a hard rock Pogo Drill (see Johnson et al. *this volume*) for local scale sampling and survey. Equally useful would be the Argo-Jason system, particularly now that it has successfully demonstrated its sampling capability. Surveys with this system, if its reality comes close to its promise, should be mandatory for deep crustal drilling. Alvin surveys would be a less satisfactory, inefficient and more costly alternative, though they would yield the minimum information needed.

Special drilling requirements

The partial offset section drilling we propose requires no new technological developments. The technological developments required for total crustal penetration are described in detail in other reports and will not be discussed here.

IV.
Primary Magmas Working Group

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Introduction and state of the art

In order to understand the nature of primary magmas that segregate from the residual mantle and then differentiate to form the upper magmatic portions of the lithosphere at mid-ocean ridges, it is imperative as a long range goal to penetrate at least one complete section of the oceanic crust and upper mantle to determine its composition. At present we cannot seismically distinguish ultramafic cumulates at the base of the crust from residual ultramafic rocks, and there is no reference drill hole by which to interpret fundamental seismic boundaries in or at the base of the crust. Both are key objectives in achieving complete penetration to the base of the oceanic crust and will fundamentally increase our understanding of the composition of the oceanic crust and its lateral heterogeneity.

There are two ways of determining the composition of the ocean crust and upper mantle. One approach would be to determine the overall structure of a heterogeneous ocean crust and upper mantle, and then drill and analyze representative continuous sections within the magmatic portion of the lithosphere to obtain its composition by mass balance. Far more difficult is to obtain representative basaltic glass samples that are the primary magma from which the crust is formed. There is little agreement on the composition of primary ocean ridge basalt and its variability due to the inherent ambiguities in deciding whether primitive mid-ocean ridge basalt glasses are primary or near primary. Some investigators feel that the composition of the most primitive magmas dredged at the ridges is close to primary, having undergone only minor shallow level crystallization. Others feel that the primary magma forming the ocean crust is highly magnesian, segregates from the mantle at great depth, and does not erupt to the surface until it has been substantially modified by fractional crystallization over a range of pressures. This question can only be resolved with any certainty by determining the nature and thickness of the earliest formed cumulates at the base of the crust and to calculate the average composition of the crust and upper mantle based on mass balance. These objectives can only be achieved by complete penetration of the crust to upper mantle levels in several deep holes. Only in this way can we begin to fully assess the composition of the oceanic crust and upper mantle and the nature, significance and interrelationship of fundamental petrological, metamorphic, and geophysical boundaries.

Major Problems

The outstanding problem recognized by the working group on primary magmas and composition of the crust is to understand the formation of oceanic crust. Specifically, we feel it is imperative to:

1 **Determine crustal stratigraphy**

2 **Identify primary magma(s)**

3 **Recognize processes which modify melt(s).**

Determine Crustal Stratigraphy

Determining crustal stratigraphy is obviously the most important baseline necessary for describing the process of formation. There remains no direct evidence concerning the nature and proportions of rock units in the crust, particularly the lower two-thirds of the crust, and their contact relationships. What are the relative proportions of basalt, dike section, gabbro, and ultramafic cumulate in "normal" oceanic crust? How do these proportions change along the strike of the ridge axis towards the fracture zones? Are these proportions constant in fast and slow-spreading centers? How do these proportions compare with ophiolite assemblages? Determination of the relative proportions of lithologies in the oceanic crust is fundamental to the determination of bulk crustal composition and for mass balance approximation of the nature of the primary melts which form oceanic crust.

Identify Primary Magma(s)

The composition of ocean ridge basalt primary magmas remains controversial. One group of experimental petrologists has argued for picritic primary magmas with MgO contents as high as 20 wt %, equilibrated with mantle peridotite at pressures as high as 25 kilobar. A second group holds that primary magmas have MgO contents as low as 10 wt % MgO and have equilibrated with mantle peridotite at 10 kilobar or less. More recently, several workers have argued for polybaric melting and segregation of magma, leading to a compositional spectrum of primary magma compositions. Determination of the composition of a total section of oceanic crust, the mineral compositions of basal cumulates and the order of appearance of cumulate phases, is necessary to constrain the composition of primary magma(s) and, by inference, their depths of segregation from the mantle.

Recognize the processes which modify melt(s).

For some geoscientists the recognition, and physico-chemical characterization, of magmatic processes is as important as the understanding of their structural and compositional products. In many ways, igneous processes (e.g. crystal fractionation, mixing, convection, diffusion, reaction with high temperature solids during transport and magma "chamber" evolution) are likely to be unique in the long-lived magmatic and tectonic environment of mid-oceanic ridges. These processes, combined to a limited extent with hydrothermal alteration, produce the chemical stratification observed and inferred in oceanic crust.

Information needed

Relative proportions, bulk composition, and mineral chemistry of the various crustal units, as well as the bulk composition and local stratigraphy of the upper mantle.

The ultimate goal is a continuous crustal core. In the short term, a series of 1 to 2 km deep holes is more feasible. In this case, it is essential that these holes be geographically associated so that interrelationships between units can be determined; i.e. the drilled extrusive rocks can reasonably be related to the drilled intrusive and upper mantle rocks. A brief summary of what we know and what we need from each unit follows:

Layer 2: Basalt

Basalts are the final magmatic product of oceanic crust formation. Petrologic and geochemical studies of dredged and drilled basalts have established many first order aspects of oceanic crust formation. For example:

1. The major role of depleted mantle sources.
2. The existence of regional scale (1000 km) lateral mantle source heterogeneities inferred from ridge basalt compositional gradients away from mantle hot spots, such as Iceland, as well as local scale (10 km) mantle heterogeneities inferred where basalts derived from depleted and enriched mantle sources are spatially associated.
3. The important role of interaction between basalt and seawater over a wide temperature range (0 to 400°C).

More than 95% of the existing petrologic-geochemical data on the oceanic crust are for basalts. These data, as well as ongoing and new projects (RIDGE) for studying basalts clearly demonstrate the importance of the oceanic crust in the global geochemical system of the earth. However, to understand the formation of oceanic crust we need information about the plutonic rocks which constitute the far more voluminous lower crust and upper mantle.

Layer 3: Plutonic rocks

These rocks form two thirds of the ocean crust, but relatively little is known of the plutonic section as dredging and shallow drilling programs have recovered insufficient samples to achieve an understanding of the deep crustal processes involved in forming the ocean crust or to infer the composition of the magmas as they come from the mantle.

Long stratigraphic sections of plutonic rock are required, and drilling is the only way to obtain such sections. Important data to be obtained and problems to be addressed are:

1. Mineralogy and mineral compositions of gabbros can be used to determine the role of magma chambers (size, longevity, and location) in creating oceanic crust. (Here we interface with the Magma Dynamics Working Group).
2. Mineralogy and mineral composition of cumulate plutonic rocks can be inverted to constrain the composition of the parental magma. Also, integration of the proportions of olivine, pyroxene and plagioclase over a stratigraphic interval of plutonic rocks can constrain the bulk compositions of the magmas forming the oceanic crust. The proportions of these phases, and their order of appearance can also be inverted to infer both the nature of the primary magma and the depth at which it initially crystallizes.
3. The bulk rock compositions of each unit can also be integrated over the depth of a drilled crustal section to arrive at an estimate of the "average" composition of the crust yeilding the

average composition of the primary magma forming the crust.

Upper mantle

The mineralogy and phase compositions of residual mantle are required to (a) determine the composition of the mantle that partially melts to create the oceanic crust, and (b) understand the processes of partial melting and melt segregation. (Interface with mantle working group).

Contact relations between the major crustal units

Particular attention should be paid to the transition zones between the major crustal units described above. These transitions are important because they are zones across which seismic velocities have a steeper gradient, and, depending upon their nature, they may also be seismic reflectors. It is vital to correlate petrologic contacts with seismic data in order to interpret existing and future seismic data in terms of crustal structure and composition. Furthermore, the petrologic Moho, i.e. the nature of the transition zone between cumulate and residual rocks at the base of the oceanic crust, may provide important information bearing on magma formation and magma transport from the mantle into the crust. Basal contacts described from ophiolites include evidence of strong fabrics indicative of plastic flow due to post-crystallization upwelling and spreading of cumulate dunite in the lowermost crust, parallel to that in the upper mantle (e.g. Casey and coworkers). Similarly, the contact between the uppermost gabbros and sheeted dikes is likely to provide essential information regarding the mode of magma transport from source to surface.

A major unresolved problem for determining the composition of the primary magma by summation of the crustal section is that the basal contact at some ophiolites is consistent with an origin for much "basal cumulate" by reaction between residual mantle and ascending melts. This replaces large proportions of residual mantle peridotite with residual mantle dunite easily confused with olivine cumulates of similar composition precipitated at the base of the crust (e.g. Nicolas and coworkers). This ambiguity leads to considerable debate about the proportion of dunite found at the base of ophiolites which should be included in estimating the bulk composition of the crust.

The stratigraphy of the oceanic crust and the crust-mantle boundary are conventionally defined on the basis of seismic data. The prevailing petrological interpretations of the seismic stratigraphy appear reasonable, however, neither the layer 2-3 or the layer 3-mantle transition zones have as yet been sampled in the oceans.

Drilling through the transition zones will not only calibrate the geophysical observations, but will address a number of fundamental petrologic problems. Studies of core samples will show to what extent the diabase/gabbro transition is also a chemical-mineralogical boundary. Studies of samples from an undisrupted layer 3/mantle transition zone will shed light on the problem of "petrologic" versus "seismic" Moho. Continuous or near continuous sections through the boundaries will also show whether these zones acted as shear zones and/or pathways for hydrothermal circulation.

Why Drill?

Currently available data do not permit solution of the problem of oceanic crustal formation. Both bulk composition (primary magma composition) and processes of chemical differentiation and stratification remain obscure.

Despite the success of ophiolite derived models as a guide to the petrologic structure of the oceanic crust and upper mantle, doubts persist about the relationship between the two. In particular, the tectonic setting of many, if not most, ophiolites remains controversial (is probably not representative of on-axis magmatism at an active mid-ocean ridge). Detailed application of ophiolite data to problems in the oceanic lithosphere must be selective and cautious. A broad consensus on the nature of primary mid-ocean ridge magmas has not emerged based on ophiolite data alone. Some ophiolites are thought to have back-arc basin or other arc-related origins. We need deep crustal rocks, from a well constrained stratigraphic context directly from the oceanic crust, in order to solve the long standing and most fundamental problem of primary magma composition(s). This can only be accomplished by drilling.

The majority of oceanic basalts have been shown to be related by low pressure crystal fractionation, and thus have evolved from primary mantle melts. Although oceanic basalts provide much information regarding the relative variability of the mantle and melting processes, and they are our most accessible windows into the mantle, they are not themselves mantle melts. Certain assumptions, such as the extent and pressure of crystal fractionation, must be made in order to invert their compositions to primary mantle melt compositions. These assumptions are uncertain, and the inversion solutions are non-unique.

Attempts to experimentally model magma formation have been largely inconclusive due to the lack of good constraints on the pressure, temperature and composition of the source, as well as the mode of liquid separation from the residue of melting.

Present sampling of the lower oceanic crust is inadequate, and is unlikely to be substantially improved by traditional sampling methods (dredging, shallow drill holes collared in volcanic rocks). The reasons for this assertion are as follows:

(1) Dredging recovers samples which have been subjected to extensive weathering at the sea water-rock interface. Mafic and, in particular, ultramafic samples are particularly susceptible to alteration in the weathering environment.

(2) The sampling by traditional methods is biased, since lower crustal rocks are only exposed on intermittent high level fault zones which protrude through the extensive debris flows covering fracture zone walls. The spacing of exposed faults is too great to provide an adequate crustal sample.

(3) Sampling by dredge is incomplete. It selectively provides rocks which have been fractured, unusual for competent plutonics, and rocks which have been pervasively altered and no longer retain strength on a hand specimen scale. Finally, such sampling can never provide continuous sections, even on the scale of meters, in the cumulate and mantle section. Continuous sections are essential to determine magma differentiation processes (vertical extent of cryptic and modal layering in cumulates), and to determine the order of crystallization of phases from differentiating magma.

The need for continuous sections on a scale of meters, tens of meters, and (ideally) hundreds of meters, can be satisfied only by drilling. Similarly, long drill holes provide the best means of sampling rock which has not been altered by sea-floor weathering.

Strategy for drilling

Although our long term goal remains a complete crustal drill hole, our first priority over the next ten years is to obtain a crustal section via offset holes in a tectonically exposed section. At an ideal site, with the present drilling technology we would have an excellent opportunity to obtain, even with moderate penetration (100-500 m), representative rocks from each of the crustal sections (e.g. basaltic pillows, sheeted dikes, gabbros, cumulate ultramafic rocks, and residual mantle), and to recover samples from the transition zones within each of these units. Petrologic and geophysical study of each of these cores would provide immediate answers to the questions of crustal petrogenesis. The results from this short term project would also be used to help with selection of one deep hole site and with the eventual interpretation of the recovered deep crustal sections.

There are obvious advantages to drilling spatially associated lower crustal sections either at or near a fracture zone. We already know of numerous sites (e.g. Vema, Hess, Atlantis II, Kane) which meet our outlined prerequisites, which are discussed below. Based on the experience at Site 735B, the probability of successful drilling and recovery of continuous core near and across the critical horizons is extremely high, even with existing technology. The drilling technology can only improve in the next 3 to 6 years making it very likely that we will be able to drill deeper and recover a higher percentage of core in a shorter period of time.

This working group reaffirms the recommendation of COSOD II that we need to immediately begin developing the capability of total crustal penetration. In this regard, we should begin selecting a site for the long term drilling initiative. Ideally, if we can agree on a site within the next 5 year period, we can begin drilling, and eventually extend this site within the next 25 years to the crust-mantle boundary.

Potential Target Areas

The most desirable site would be one where all crustal elements and a segment of upper mantle are represented in a stratigraphic sequence. The Vema FZ (Fig. 4-1) would be a possible example of one such site. In this case four holes as follows would cover our objectives: 1) to transect the volcanic-sheeted dike interface, 2) to transect the sheeted dike gabbro interface and extend into gabbros, 3) to penetrate the gabbro-ultramafic cumulate boundary and extend through the ultramafic cumulates, and 4) to begin and extend a significant distance into the mantle peridotites.

Hole priority would depend on the configuration of units at the site chosen but in the case of the Vema site would be as shown in Fig. 4-1. Representative coverage of the crustal section could be expected to be obtained with four holes each of about one kilometer length.

The following areas potentially include all or most of the desirable characteristics outlined above. They are listed in order of priority, though we stress that improved knowledge of the areas may well change their ranking.

(1) Vema FZ (9-10°N) or tectonically similar region (Atlantic), with geochemically normal crust and slow spreading rate.

(2) Hess Deep (Pacific), geochemically normal, fast-spreading.

(3) Atlantis II, Indian Ocean, geochemically normal, slow spreading

(4) Kane, 23°N, Atlantic, geochemically normal, slow spreading (Mark area)

(5) 15°20'N, Atlantic, geochemically enriched, slow spreading

(6) Garrett, South Pacific, geochemically normal (?), fast-spreading

Vema Fracture Zone The section investigated using the French submersible is on the transverse ridge south of the active transform. Although gabbroic and ultramafic cumulates are shown on the idealized cross-section, the gabbros sampled appear to be coarse-grained, pegmatoid gabbros with Fe-Ti oxides characteristic of the uppermost gabbros in ophiolites. The currently preferred hypothesis is that the gabbro - mantle peridotite contact is a tectonic one. Gabbros show hydrothermal alteration typical of dredged gabbros in many fracture zones. The contact between layer 2 and layer 3 is thought to be igneous rather than tectonic (C. Mevel, pers. comm.).

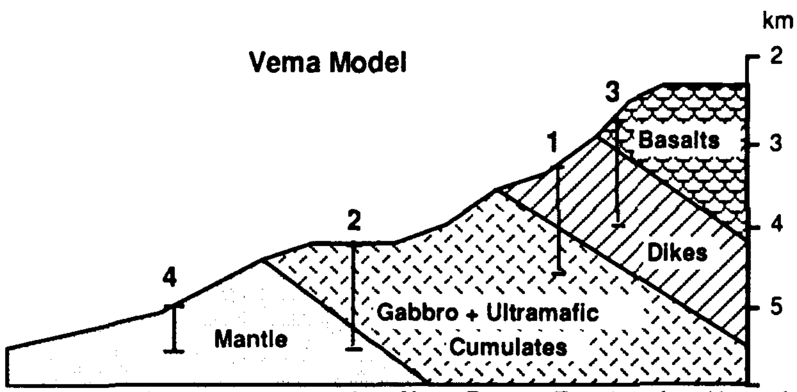

Fig. 4-1 Idealized cross-section of the Vema Fracture Zone based on (Auzende et al., 1989) showing potential drill sites.

Hess Deep Hess deep is a 5-6 kilometer deep which terminates the Galapagos spreading center 10 to 20 km east of the East Pacific Rise. No adequate site survey reports are currently available, but it is known that layer 3 rocks have been dredged by Russian scientists and that deep crustal sections have recently been observed by a French submersible. In addition, Peter Lonsdale and co-workers have a dive program to the region pending which may provide an adequate site survey.

This site is of considerable interest, as it appears to reflect simple, amagmatic (or low magmatic) rifting at the termination of the Galapagos spreading center, exposing deep crust formed at the East Pacific Rise. It is remote from transforms, hot spots, or other known anomalies, and has the potential of being the least complicated natural exposure available.

Atlantis II Fracture Zone The Atlantis II F.Z. is one of the major N-S trending fracture zones of the slow-spreading SW Indian ridge. The crust has a normal composition, possibly representing the regional depleted N-type MORB end member (Snow et al. 1987). Earlier attempts to drill ultramafic rocks within the Atlantis II F.Z. failed (sites 732-734, ODP Leg 118) but Hole 735B on the eastern flank of the FZ was extremely successful. An almost continuous 500 m section of gabbroic layer 3 has been drilled with 87% overall recovery. One additional leg devoted to deepening hole 735B would give another 500 to 600 m through presumably deeper levels of layer 3. Penetration of the layer 3-4 transition zone at hole 735B might be achieved with present drilling technology. Additional site survey and submersible studies are needed to locate drilling sites needed to sample the layer 2-3 boundary in a shallow (<500 m) hole.

Kane Fracture Zone The spreading axis south of the Kane F. Z. was drilled in Leg 106 and 109. DSDP site 392 is located on basaltic crust on an equivalent flow line to the MARK area. A complete section of crust is expected in the region between the eastern nodal basin of the Kane F. Z. and the central high drilled by legs 106 & 109. A transect of holes from the western wall towards the center of ridge axis should satisfy the Vema Fracture Zone model for a complete section (Fig. 4-1). Only petrologically normal basalts have been sampled from Kane Fracture Zone. Active hydrothermal vents (Snake Pit) are located in ridge axis, and high temperature hydrothermally altered rocks have been sampled from the western wall of this spreading center. Spreading in this region is currently amagmatic.

15°20' N FZ The 15°20'N Fracture Zone lies within a segment of the mid-Atlantic ridge characterized by incompatible element enriched basalts (E-Type mid-ocean ridge basalt). Between 13°N and 16°N, Soviet and French groups have recovered enriched samples from volcanic, plutonic and ultramafic sections. Initial data show that these samples are compositionally related. This geochemical anomaly correlates with a shallow bathymetric anomaly. Further investigations are in progress, including a Soviet submersible survey.

Garrett FZ The Garrett FZ is a major transform fault located in the fastest-spreading portion of the southern East Pacific Rise. Peridotites and gabbros were recovered from this site (Herbert et al. 1983, Gallo et al.,pers. comm.). Sea Beam and Sea Mark II surveys are available, and zero-age basalts have recently been dredged from the region by Sinton et al. (pers. comm.).

Requirements

Given the Vema F.Z. model, our objectives might be attained with 4 holes of approximately 1 to 1.5 km length. The target should be easily accessible for intensive site surveys, seismic profiling, submersible studies, etc. The existing site surveying is presently most advanced for the Vema, Kane and Atlantis II targets. All holes will probably require bare rock spud in and should involve combined RCB and high speed diamond drilling technology.

V. Magmatic Processes Working Group

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Preamble

In the following discussion, we assume that no single drilling site will solve all the problems of magmatic processes recorded by deep ocean crust and shallow mantle. However, we feel sure that one site probably **can** eliminate many hypotheses and greatly advance our knowledge. Obviously, the quality of our constraints will improve as the number and variety of samples increase.

State of the Art

The existing sample record of the lower oceanic crust and upper mantle exists in dredge hauls and several drill penetrations of gabbro. We do not enumerate these here, as they are common property. Likewise, we mention only the obvious fact that the voluminous record of ocean basaltic volcanism provides us with multiple working hypotheses about the nature and origin of deep ocean crust and depleted mantle.

Of greater import to prospective crustal drilling is the fact that the last decade has seen a surge of progress in the understanding of magmatic processes in terms of data, experiment, and theory. Examples are data from layered intrusions and lava lakes oriented increasingly toward well-defined problems, experiments in both aqueous solutions and silicate melts, and considerable progress in theoretical understanding constrained by the harsh realities of field evidence. As an illustration of how detailed studies can constrain hypotheses, we may cite the experiment done by Browning (see abstract, this volume) in a 20-meter core from hole C-4 on Cyprus. Here, a close spacing of magma pulses is reflected in sawtooth variations of mineral composition up the stratigraphic section, and the data successfully eliminate the hypothesis that these layers of rock are the product of a single, large, well-mixed body of magma. The data do not exclude several other scenarios of local liquid segregation capped by liquid or solid strata.

Outstanding Problems

1. We need to characterize plutonic crustal rocks.

A fundamental problem which can be addressed by ocean crustal drilling is the nature of the plutonic rocks in the oceanic crust. This must be addressed before the associated problems concerned with magma chamber processes can be answered. Hole 735B was successful in providing evidence for relatively unaltered gabbroic rocks in at least the upper portion of oceanic layer 3, although the remainder of the lower crust at this location remains unexplored. Indeed, the material contained in Hole 735B may only represent a small fraction of the plutonic ocean crust. Although dredge samples have in the past provided us with information regarding magmatic processes related to ocean crust formation, their usefulness has been severely restricted by chemical alteration and lack of stratigraphic control. They may also represent a biased sampling of the lower oceanic crust.

Detailed studies of the eruptive products at spreading ridges have provided predictive models for the types of plutonic rocks which may be present in the oceanic crust. Current knowledge regarding the overall composition, mineralogy and structure of the lower oceanic crust suggests that much can be gained by comparison to terrestrial mafic layered intrusions where the rock signatures associated with various magmatic processes have been investigated. In this sense, a continuous section of core may be the only means by which questions regarding fine- and gross-scale structural layering and their relation to the magmatic evolution of the ocean crust may be resolved. A continuous section of core will provide the information necessary to evaluate the types of chemical and structural gradients such as those seen in terrestrial mafic layered intrusions. As yet, the information extracted from studies of ophiolites has been fraught with uncertainty regarding the influence of post-ocean crust-forming events (including obduction processes) as well as the general validity of ophiolites suites as analogs to typical oceanic crust. A complete section through layer 3 and into the residual mantle would provide a rigorous test of all of these hypotheses, which relate magmatic products to the processes responsible for them.

Characterization of ocean crust plutonic rocks for the purpose of evaluating magmatic processes will require a large number of observations and will involve a number of analytical techniques. The major element, trace element, and isotopic compositions of the rocks will need to be determined, as well as the major and trace element compositions of the minerals in them. Such textural features as modes, grain sizes, grain shapes, and grain orientations, will have to be described and quantified in terms of both averages and distributions of values. Descriptions of cumulus minerals, intercumulus minerals, and post-cumulus reaction relationships will be critical to interpretations of the crystallization history of these rocks. Variations in these compositional and textural features will need to be determined over a range of scales from centimeters to tens or hundreds of meters in order to evaluate the nature of abrupt and gradational changes in these parameters. The orientation of gradients and abrupt changes may help divide rocks into roof, floor, and sidewall sequences, and ultimately provide information on the geometry of magma chambers.

2. Did these rocks form in a magma chamber and can the geometry of the chamber be constrained?

There are certain petrological criteria that allow us to infer confidently that an igneous rock formed in an environment of slow cooling. For example, coarse-grained textures effectively preclude rapid cooling rates. The rock types and structures found in well-studied continental layered intrusions represent the products of slowly cooled magma reservoirs. By analogy, the identification of similar features in oceanic plutonic rocks would lead us to propose that the oceanic rocks formed in the same way. The failure of cumulate plutonic rocks to match any reasonable liquid composition points to an origin in a fractionating magma chamber, as does the recognition of significant proportions of trapped intercumulus liquid.

The geometry of a magma chamber can be constrained by textural, structural and geochemical information. Various unidirectional primary solidification features (such as harrisites or comb layering) allow the orientation of a cooling surface to be inferred. The attitudes of macroscopic features such as finger structures may also indicate whether a plutonic rock formed on the roof, walls or floor of a magma chamber. If depositional features such as cross-beds can be unambiguously identified, they may also be used to define the direction of stratigraphic-up in a sequence of layering. This in turn defines the orientation of the magma chamber margin where the depositional feature accumulated. The gross stratigraphic ordering of drilled plutonic cumulates is also important. The down-hole repetition of the sequence isotropic gabbro - layered gabbroic cumulate - layered ultramafic cumulate would be suggestive of multiple, stacked magma chambers. If the latter sequence was only penetrated once in a deep drill hole (say, 2 km deep), or if only parts of the sequence were encountered, that would be suggestive of a single crustal-level magma chamber. The base of the plutonic sequence may reveal the presence of a magma feeder system, perhaps cutting the basal cumulates. Such an observation would place limits on the lower boundary and thickness of a magma chamber, as well as demonstrating the link between partial melts supplied from the mantle and fractionating liquids in magma chambers. Cryptic variation on a range of scales can provide information on the vertical extent of a magma body. In particular, rapid variation of mineral chemistry with height cannot be reconciled with a large, well-mixed magma chamber. Lastly, geophysical methods such as seismic tomography, electromagnetic deep sounding, and gravity modeling, will provide an essential adjunct to petrological studies. These geophysical techniques will provide the larger-scale framework upon which our petrological modeling of magma chamber geometry will build.

3. Under what physical conditions and by what magmatic processes did layer 3 evolve?

Specific magmatic processes responsible for formation of layer 3 are largely inferred from studies of sea floor basalts, terrestrial layered intrusions and ophiolites. Study of the plutonic sequences associated with the extrusive series can help eliminate or augment hypotheses associated with the cause of variation owing to fractionation, mixing, recharge, assimilation, eruption and degassing. Evidence from the study of layered intrusions such as the Stillwater and Bushveld complexes illustrate that influxes of magmas of distinct chemical and isotopic composition and their fractionation history can be inferred from the stratigraphic record. Magmatic processes inferred from the study of ophiolite complexes, such as recharge and magma mixing, need to be assessed as to their applicability to the mid-ocean ridge magmatic system. By looking at a continuous section, one can constrain spatial and temporal gradients in intensive parameters and composition on widely different scales. For example, comparative studies of erupted basalts and mantle assemblages suggest that oxygen fugacities of mantle-derived melts have become more oxidized during degassing in shallow chambers. If so, stratigraphic variation in oxygen fugacities should be recorded in mineral assemblages in layer 3. Combining information from the plutonic suite with data from both mantle assemblages and the extrusive rocks is required to constrain the magmatic evolution of the ocean crust.

Studies of layered intrusions indicate that a complete interpretation requires full understanding of those changes that have affected the cumulates during the entire history of solidification. As an example, interstitial melt commonly evolves by reaction with cumulates during cooling. The evolved intercumulus melt may escape from the pile to mix back into melts and become an important component of the melts that eventually erupt on the sea floor. An understanding of post-cumulus processes such as infiltration metasomatism, textural evolution and low-temperature re-equilibration is essential for reconstructing cooling rates and the timing of influx events (from magma influxes to subsolidus metasomatic events). The spatial and temporal variations in these parameters are fundamental in interpreting cooling (crystallization) rates, thermal structure and evolution of the deep ocean crust. If recharge rates are sufficient to prevent significant melt evolution in a given thermal regime, one may find thick cumulate sequences with limited compositional variation. By understanding the gradients of various intensive parameters one may infer the rates at which processes of interest occur.

4. How many primary magmas were there and how do they relate to the volcanic sequences?

The chemical evidence of multiple primary magmas at ocean rifts includes; crossing rare earth element patterns (Langmuir et al. 1977), variable Sr and Nd isotope ratios, and parallel liquid lines of descent at single locations. Knowing the major and trace element composition of these primary magmas is required to understand mantle processes such as amount of partial melting and to understand mantle heterogeneity. The major and trace element chemistry of the primary magmas have been inferred from the erupted lavas assuming that certain magma chamber features and processes are understood. These features and processes which include the size of the magma chamber, the amount of recharge (primitive magma), the amount of fractional crystallization, the volume and composition of assimilated material, and the eruption rate, however, are poorly understood.

As a first order approximation the number of primary magmas may be estimated by looking at the trace element variation in the most primitive minerals in the cumulates. The ratio of volume of the magma chamber to the recharge volume may be inferred from the mineralogical and chemical variation in the cumulate layers. The recharge rate may also be estimated by knowing the modal abundances of the cumulate minerals (higher modal olivine requires a higher recharge rate). The amount of fractional crystallization can be estimated as the ratio of the thickness of the cumulates relative to the thickness of the erupted lavas. The composition of potential assimilants can be determined if the roof of the magma chamber is collected. The volume of assimilant can be estimated using mixing models and conserved chemical components. Finally, the chance exists that mafic segregates representing primary magmas may be found as has been the case in ophiolites.

Information Needed

1) A continuous section with significant amounts of unaltered core is needed, A completely unbroken record is an unrealistic and unessential goal, but local continuity over lengths of meters to hundreds of meters is essential to a valid interpretation of the magmatic record.
2) Modal stratigraphy, i.e. the percentage of each mineral with height in the column, is the fundamental base line on which all igneous interpretation rests. This is provided by standard microscopic and imaging techniques on thin sections and sawn core faces. A continuous record of the core is desirable.
3) The stacking sequence imposed by faulting will need to be known in order to flag natural discontinuities in the magmatic-stratigraphic record.
4) Cryptic mineral variation (change in chemical composition) must be known at a variety of scale lengths from micrometers to kilometers, depending on the problem to be solved. This information is routinely available through electron and ion microprobing and imaging of polished thin sections. The observed variation will yield (through inversion procedures) the chemical composition of the parental and interstitial liquids.
5) Textures and fabrics must be known in order to interpret how mineral grains, accumulated, grew, interacted with liquid, compacted, deformed, and solidified to rock. Such features may also yield sites for sampling trapped liquid for comparison with erupted lavas.
6) With bulk rock geochemistry we obtain crucial information on magmatic evolution and the local inventory of element concentrations furnished by accumulated crystals and interstitial liquids. These relate both to the evolution of the magma bodies and to the local process of solidification. Isotopic geochemistry provides the fundamental tracers of magmatic processes and provides an important link

(or perhaps a failed link!) to extrusive lavas and depleted mantle.

7) Spatial variation of crust in the lateral dimension can be understood only with cores from multiple sites. A one-dimensional view from a single site would provide valuable constraints, but these would improve with geographic breadth and variety of tectonic regime.

8) Physical properties of core rock are of interest for magmatic processes, and in particular, the orientation of the core should be known wherever feasible. Once this is learned in a given section, it may be carried forward via core fabric within a given fabric unit.

9) The age of crustal rocks is highly desirable, especially for correlation with erupted lava and mantle. If feasible, this should be obtained. We note the recent success of uranium-lead dating of zircons from trondjhemitic veins in the Hole 735B gabbros. This suggests that dating plutonic rock sections may encounter fewer problems than found for oceanic basalts.

Workup Time and Research Design

In reviewing the state of the art, an example was cited of a drill core from Cyprus. For this study, the research design required an investment of 1 man-year for every 10 m of core. Not all segments of core are equally demanding, but it is quite conceivable that a full understanding of a single section of crust to the upper mantle would require an effort of order 100 man-years. We mention this only to emphasize that it will be a futile exercise to drill a long core at great cost without providing for the long-term support of research, on a competitive basis, by research teams and individuals. Curation, sample allocation, and coordination of efforts similar to the best of those in the lunar program may be pertinent. Existing practices may work in principle, but care should be taken that doors are opened to qualified investigators without undue impedance from territoriality or a misplaced desire to avoid redundancy. A little redundancy may be worth the risk.

Why Drill?

Implicit in all the above statements are defenses of the following propositions.

1) Continuity and stratigraphic control are essential to the demonstration that the rocks constitute a coherent package, for example, to demonstrate whether the youngest are on top.

2) Core samples will be more pristine than dredge samples and hence fresh enough to illuminate critical igneous problems.

3) Dredge samples are nearly unobtainable at fast spreading centers, where drilling provides the only access to samples.

4) The various rocks from the lowermost crust and upper mantle are poorly represented in dredge hauls with relative abundances likely reflecting ease of dredging rather than true outcrop proportions, whereas drilling provides an unbiased sample of these rocks.

Drilling Strategies

Main Objectives:

1) Our main objective is to obtain a long section (constructed from a number of 300-500 m holes) of core through most of layer 3 in at least one location. The need to reconstruct at least one magmatic section far outweighs our requirement for sections in different tectonic regimes.

2) Long sections through layer 3 may not automatically result in a good section through the Moho. Our second priority should be a good, relatively complete section through the lowermost magmatic sequence and the uppermost mantle. This will likely require a separate leg and very specific site survey work.

3) Our third priority is to recover crustal material formed at a fast-spreading ridge (assuming that objectives 1 and 2 will most likely be attacked in slow-spreading environments). Ideally, a composite section would be obtained in several 300-500 m holes. Realistically, this will probably be one or two holes (in both gabbros and peridotite) to constrain variations due to spreading-rate.

4) A fourth priority is to obtain cores from crust of different ages that formed along a single flow line.

General Strategy

This discussion assumes a program in which there will be 6 legs or so devoted to problems that require drilling the deeper portions of the ocean crust. Given present technologies and resources, a single hole through the entire crust is precluded. A 6-leg program will need to address at least some of the concerns of geophysicists, petrologists and chemists. We believe that the best approach is one of drilling a series of 300-500 m offset holes. A 4-leg program using such an approach could produce one complete section through layer 3, including the crust-mantle transition, and perhaps a partial section through fast-

Pros and Cons of Different Sites

Strategies	Site	Pros	Cons
1A, 1B	Hess Deep	Complete crustal section non-transform crust	Deep water and steep scarps little detailed survey
1A, 1B	Vema FZ	Complete crustal section lots of site work	Nature of contacts unknown, tectonic disruption? Fracture zone
1B	735B	Excellent drilling conditions, 500 m open hole exists, shallow water	Crustal structure not well known
1A,1B	MARK-Kane	Peridotite-gabbro, lot of site work, transform to non-transform exposures	No upper section?
1A,1B,2	Mathematicians	Crustal exposures, fast spreading, non-transform	Little detailed work dying ridge overprint
2	Garrett FZ	Crustal exposures, very-fast spreading, some site work	Setting of gabbros unknown
1A	418	Layer 2-3, good drilling record and core recovery	Geographically "separated"

spreading crust. Another 2 legs (or more) could be used for deep mantle drilling or for examining the Layer 2-3 transition.

A strategy of drilling offset holes maximizes our chances of recovering samples of all parts of the oceanic crust. The degree and style of faulting in many slow-spreading ridges may well preclude finding a single site to drill a 1500 m core. An offset drilling strategy provides more flexibility in planning drilling legs and in modifying those plans at sea.

We advocate a four leg program in the following format:

1) Obtain a composite section through most of layer 3 at a single site.

a.) A 2-leg program to drill four 300-500 m holes from the base of Layer 2 into the uppermost mantle at crust of similar age in the same fracture zone or ridge environment.

b.) A single leg to drill one long hole through the Moho. The holes drilled to satisfy (a) may not penetrate the Moho. A leg should be devoted specifically to a site at which we're reasonably confident that a magmatic transition between layer 3 and the mantle exists.

2) Obtain a reference section in fast-spreading crust (or at least crust of the opposite tectonic extreme from that drilled in 1). One leg to drill two 300-500 m holes in tectonically exposed layer 3.

Possible Targets

Before any target is drilled we need convincing evidence for an exposed, complete crustal section. There must be suitable benches or platforms on which a hard-rock base can be deployed. Ideally we would also have some indication that the unit contacts are magmatic rather than tectonic--i.e. the section has not been significantly disrupted by tectonic processes.

Site Survey Requirements

We need to know the geological and geophysical setting of any potential drill site. This involves detailed bathymetric, seismic, magnetic, gravity and dredging surveys on a local and regional scale. From these data promising sites can be examined at higher resolution--with side-scan sonar, submersibles, or Argo-Jason. In addition to the site survey data, taken heretofore, drilling composite sections will require detailed photo-mosaics of potential drill sites and several back-up sites on well-located benches or outcrops. We should mark these sites with long-life transponders. We also have to have well-located (i.e. submersible, Jason, or pogo drill) samples from the benches and outcrops so that we can identify stratigraphic location from petrologic and structural data. Obtaining these data will take more than one cruise for each region proposed for drilling the composite crustal sections.

VI. Tectonics and Rock Deformation Working Group

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Introduction

The inherent tectonic/structural character of the ocean lithosphere remains relatively unknown, except by analogy to ophiolites, due to a lack of in-situ sampling of the deep crust and shallow mantle. Numerous physiographic and geophysical studies over the past decade, however, have resulted in a major change in our view of the magmatic and structural processes operating at mid-ocean ridges. For many years models for crustal formation at ocean ridges were guided by a relatively simple paradigm: with the crust viewed effectively as an "infinite onion" continuously formed by eruption from and crystallization around a steady-state magma chamber undergoing continuous extension beneath the ridge axis. This model is now viewed as inadequate, particularly for slow-spreading ocean ridges, where magma chambers are believed ephemeral, with long intervening periods of amagmatic extension producing major structural disruptions of any simple "magmatic" stratigraphy. Differences in crustal structure between slow and fast spreading ridges suggest a need for multiple working models to explain the full spectrum of ocean crust structure and physiography.

Of particular interest to this working group were the numerous features of the Mid-Atlantic and other slow-spreading ridges unexplained by the infinite onion model developed for faster spreading ridges. Such features include deep rift valleys, the presence of plutonic rocks commonly exposed along rift valley walls, and the presence of plutonic breccias in a number of shallow drill holes (footwall talus breccias?). Huge uplifts, possibly on large low-angle faults as have been partially documented near the Kane Fracture Zone (see Fig. 3-1), have exposed massive plutonic rocks in the rift mountains. Recent multi-channel seismic reflection surveys in the western Atlantic have shown that the lower crust is pervaded by planar reflectors dipping at around 30°. One interpretation is that some of these are low-angle faults that sole into the Moho. This suggests the possibility that the Moho may be a structural boundary. Microearthquakes have been recorded in the uppermost mantle beneath the Mid-Atlantic Ridge, which indicates that brittle faulting, and probably fluid circulation exist there. The later can result in the formation of hydrous phases such as talc, tremolite, and/or serpentine along the faults, critically modifying the structural rigidity of the deep crust and mantle. The presence of serpentinite is important not only for the velocity structure of the crust, but also as a potential source for magnetic anomalies.

Whether or not master faults are present, there is still the question of whether all, or part of, the crust is strongly tilted, and what fault geometry exists below the sea floor (e.g., curved or listric). Because brittle faulting involves dilation, faults will also be pathways for fluids and this is evident in the oceans from the localization of modern hot springs along fissures and faults. Below the zone of hydrostatic circulation, high pore fluid pressures may cause episodic brittle failure and allow fluids to drain upwards. Increasing temperatures with depth, however, should eventually favor crystal-plastic flow in ductile shear zones. In addition recent seismic studies have suggested that major fault classes may exist which have formed outside the rift valley domain.

Given the remarkable complexity and variety of crustal structure now believed to exist, there seems little hope that it, and the processes which form it, can be fully evaluated without the critical three dimensional information uniquely provided by drilling. Drilling will provide critical information on the geometry of amagmatic and magmatic extension as well as documenting the nature of faulting and the character of reflectors formed outside the rift valley environment. In particular it could confirm the presence or absence of low-angle faults corresponding to the recently observed seismic reflectors, providing fundamental insights into the accretion-deformation history of the crust. *In-situ* samples of the deep crust and shallow mantle will provide samples from which the physical properties of the deep crust and mantle as well as the principal creep mechanisms operating during crustal extension, rift mountain formation and lithospheric necking can be directly determined. These can then be correlated directly to seismically observed properties of the ocean crust, such as anisotropy in the lithosphere, allowing more confident use of geophysical observations in exploring the oceanic lithosphere. It should also provide information on changes in extension at a site as isotherms rise and fall in response to formation and freezing of magma chambers. Freezing should result in deepening of the zone of brittle faulting and associated hydrothermal circulation. In drill core, such a change might be evident from retrogressive hydrothermal metamorphism (which is evident in many oceanic and ophiolitic high-level gabbros) associated with faults or fractures. When a new magmatic cycle is superimposed on structurally extended crust, cross-cutting dikes and veins, prograde hydrothermal metamorphism and complex structural relationships may result. Several of these cycles may occur to produce crust drilled at one site.

Outstanding Problems

1. What is the oceanic Moho?

The Moho is one of the fundamental interfaces within the Earth and yet our current understanding is extremely limited.

Current knowledge: The Moho is a reflector of seismic energy and a velocity discontinuity for compressional waves. Some dipping reflectors within oceanic crust appear to sole into the Moho.

Hypotheses: Three principle hypotheses exist as to the nature of the Moho: 1. The Moho is an igneous compositional boundary (transition between fresh gabbroic and ultramafic lithologies) 2. The Moho is a metamorphic feature (serpentinization limit of ultramafic rocks. 3. The Moho is a structural feature (e.g. a decollément or deformation boundary).

Implications: 1. The Moho formed by igneous processes possibly due to crystallization of magmas in a chamber above the mantle upwelling at a ridge. 2. Alternatively hydrous fluids may penetrate the entire oceanic crust, and whole-crustal hydrothermal convection cells may be possible. 3. The Moho is purely a structural contact from which no direct petrogenetic inferences can be drawn.

2. What are the tectonic processes that shape mid-ocean ridges?

What are the respective roles of brittle faulting, ductile deformation and magmatism?

1. Are significantly different mechanisms of extension active at different magma supply rates (e.g. dike injection vs. deep faulting)?
   a. What is the relationship of purported asymmetric low-angle faults (detachments?) to magma supply and ridge segmentation?
      i. Are asymmetric low-angle faults formed during amagmatic extension? On slow-spreading ridges only? Only near fracture zones?
      ii. How continuous are low-angle faults along ridge strike?
   b. Are low-angle faults responsible for lower crustal and mantle exposures?
   c. Do low-angle faults control the morphology (topography) of ridges, rather than mantle dynamics or steep faulting?
   d. Are they responsible for periodic topographic variations orthogonal to ridge strike?
   e. Can they be correlated with the low-angle seismic reflectors observed in the western Atlantic?
2. How do faults change with depth (fault morphology, geometry, width, fluid interactions)?
3. How do faults change with time (progressive deepening of brittle/ductile transition resulting in ductile faults overprinted by late brittle faulting.)?

3. How does deformation affect the circulation in the crust, and vice versa?

Hypersolidus Deformation (deformation within a partially molten zone)

Current knowledge: Experiments show that deformation at hypersolidus conditions influences liquid segregation and that deformation in the presence of liquid can cause fracturing.

Hypothesis: Deformation at hypersolidus conditions should produce liquid segregation in small-scale dilatational fault zones, and on a larger scale, liquid pools should form at the top of the partially molten zone below the zone of crystal-plastic deformation.

Implications: The orientations and distribution of fractures should allow determination of the stress field at the time of fracture. The orientations and distribution of fractures may control liquid flux. Large-scale lateral movement of liquids throughout the partially molten zone is possible. Liquid segregation could drive fracturing, and the strength of the fractured zone could be small. This partially molten, fractured zone could be a strong reflector.

Deformation-induced liquid segregation can occur in the partially molten zone. The liquid can potentially be trapped at the boundary of the partially molten zone, where the deformation changes from dilatational cracking to non-dilatational, subsolidus, crystal-plastic deformation. This means a layer of liquid and a layer of restite could form at this boundary. This stratification should produce vertical velocity variations, and a strong reflector or reflectors, depending on the scale of observation. The evidence for the structural generation of this layering might be cryptic. The refractory material left behind during partial melting should be stronger and chemically distinct.

Deformation at subsolidus, high-temperature conditions

Current knowledge: Experiments and field studies of continental lithosphere show that deformation is commonly concentrated into crystal-plastic shear zones.

Hypothesis: Deformation at these conditions should be non-dilatational crystal plasticity, and regardless of whether the deformation is homogeneous or partitioned into shear zones, liquid migration should be inhibited.

Implications: Localization of deformation in shear zones occurs because dynamic recrystallization of constituent minerals leads to strain softening. The bulk crustal rheology may be controlled by the presence of shear zones, and the shear zones may form the dipping seismic reflectors imaged in oceanic crust. Crystal plastic deformation will produce preferred orientations of minerals that should form strong reflectors.

Deformation at subsolidus, low-temperature conditions

Current knowledge: Rocks deform at low temperatures by fracturing, and any fluids that are present will flow along the fractures.

Hypothesis: Brittle deformation at low temperatures should lead to pervasive fluid migration and hydrothermal alteration.

Implications: The fractured, dilatant zone should allow fluid penetration. This will result in advection of heat by fluid flow, and change the thermal structure of oceanic crust. The presence of fluids along fractures affects deformation in several ways: changing sliding resistance, neocrystallization of weak phases, and hydrolytic weakening are all possible.

The depth of the transition from bulk brittle to ductile behavior can be predicted from a known thermal gradient and rheological models, and the prediction can be tested by drilling. This is important because of our current reliance upon the extrapolation of rheological data from experimental to geologic conditions to derive tectonic models. The depth of the brittle/ductile transition determines the elastic thickness of oceanic lithosphere.

4. How are the spatial distribution and focal mechanisms of earthquakes and aspects of the velocity structure rationalized in terms of the brittle-ductile transition?

Variations in the seismic velocity in the oceanic crust are influenced by the distribution of fractures with depth. For example, the 'layer 2-3' transition is, from analogy with ophiolites, a contact between sheeted dikes above and 'isotropic' gabbros below: dikes and gabbros that are mineralogically similar but differ in the degree of brittle deformation and associated alteration during ridge extension. Does the layer 2-3 transition map the depth to the brittle-ductile transition at the time of crustal accretion and extension at mid-ocean ridges? We clearly need guidance on the physical conditions (temperature, strain rate, pressure and fluid pressure) at the time these rocks were actively deforming so that we might apply this insight on the conditions at the brittle-ductile transition to other applications such as the depth distribution of earthquakes. The seismicity observed at fast and slow ridges implies significant differences in the strength-depth curves at these end members which presumably result from their different thermal-magmatic structures. However, current models for strength-depth curves within the crust are based on experimental results on hand samples which ignore the importance of localized zones of low-shear strength within the crust. These zones of failure may also exert significant control on the nature of flexure of oceanic lithosphere associated with large mid-plate loads or subduction of the lithosphere. Deep drilling and logging will permit the identification of *in-situ* failure mechanisms and rates of deformation that determine whether failure occurs brittlely or ductilely and determine the significance of localized zones of deformation. Brittle-ductile zones of deformation and fault zones represent strong candidates for fluid migration and the generation of large amplitude seismic reflections within the igneous oceanic crust.

5. What is the stress state & rheology of lower crust and mantle near active transform faults and other settings?

A. Away from faults.
   1. Stress
      a. What is the state of stress in relation to the ridge as a function of depth?
      b. With the removal of hydrostatic overburden, is the overall stress tensional (slab-pull) or compressional (ridge-push)?

c. Is there a significant compressional to tensional stress change with depth, implying a bending moment induced by cooling?
d. Is there any component of non-ridge-parallel stress that might reflect wither asthenosphere forces or plate boundary forces?
2. Rheology
a. What is the nature of the brittle to ductile transition with depth?
b. Are any significant faults encountered and what is their orientation with the ridge?
c. Do deep faults correlate with seismic reflectors?

B. Near transform faults.
1. Stress
a. Is there a significant component of stress parallel to the fault from a strong fault surface, or is the fault weak, resulting in purely normal stress?
b. Is the dominant fault-normal stress tensional, implying a relative importance of thermal cooling stress, or compressional, possibly reflecting an in-progress plate reorganization?
c. Is there a vertical gradient in either the absolute state of stress (tensional to compressional), signifying the importance of thermal bending moments, or in the direction of principle stress, possibly signifying the importance of asthenospheric forces?
2. Rheology
a. Is there a significant change from brittle to ductile rheology with depth?
b. Are any significant faults encountered ?
3. Anisotropy
a. Is there a development of velocity anisotropy associated with any of the stress or rheology gradients?

What information do we need and why drill to get it?

To engage the questions enumerated above, we need the following information and samples:

A. Oriented and continuous core!
1. We need to establish the kinematics of deformation within the lower crust and upper mantle which requires the establishment of a spatial continuity and orientation in relation to known tectonic features in the ocean basins, such as ridges and transform faults. Measurements of displacements and strains in faults, ductile shear zones, joints and dikes help establish this kinematic framework.
2. We want to infer the rheological laws for deformation in deep oceanic rocks by deducing the controlling physical mechanism from study of the diagnostic deformation structures on the mesoscopic and microscopic scales. Constraining the rheology of these rocks would then allow us to estimate the *in-situ* stress and driving forces involved in sea floor spreading and transform faulting.
3. We need paleomagnetic constraints on the tilting of crustal blocks in the extensional settings of mid-ocean ridges.
4. We want to know the distribution of fluids as deduced form metasomatic and alteration effects.
5. The elastic properties of fault and shear zones should be measured so that we may properly evaluate these structures as candidates for the reflection structures of the lower crust and Moho.
6. We want to measure the development of mineral preferred orientation in deformed mantle rocks in the context of plate kinematics so that we can better understand the velocity anisotropy and particle-motion anomalies in seismic observations in the ocean basins.

B. Down-hole physical logging is an essential activity to accompany and augment the acquisition of core. We want to measure:
1. *in-situ* stress in relation to the tectonic setting.
2. Permeability and heat flow especially in active sites, to determine the effectiveness of hydrothermal heat transport along faults.
3. There is a pressing need for logging of borehole structures that allow us to orient core by correlating planar features.

C. Down-hole geophysical instruments, especially seismometers, should be deployed in the drilled holes in active areas. This will help us place the drill site in its tectonic context.

D. Seismic - We recognize that drilling represents the best test of whether important seismic reflections in Mesozoic crust in the NW Atlantic ocean represent fault planes/localized shear zones. Given our inability to sample (drill) the lower crust in this region for the foreseeable future, however, we must perform detailed seismic surveys of drill sites that will attempt to map seismic boundaries to be encountered in the drill holes. A variety of seismic methods exist for these surveys. High resolution refraction surveys of potential drill sites will help design drilling programs by determining depths to seismic boundaries (e.g. 2-3, Moho). Pre-drilling reconnaissance reflection profiling may define reflection horizons. Once the hole has been drilled, vertical seismic profiles will determine whether reflective horizons (if any) correspond to localized zones of deformation or other interfaces. If reflections can be identified in the VSP data, a high-resolution seismic reflection survey, possible deep-towed, should be performed to establish whether the reflective horizons can be mapped away from the drill hole to constrain the geometry of the reflector. For closely spaced drill holes, it would also be possible to conduct borehole-to-borehole

Table I Suggested Site Survey Studies and Tools	
1. Regional Bathymetry (10's of km) a. Sea Beam b. Sea Mark II	2. Regional Geophysics (5-10 Km spacing) a. Magnetics b. Gravity
3. Regional Geophysics (near site) a. Heat Flow b. Seismic refraction c. Deep-tow seismic array	4. Intermediate Scale Mapping (100' m+ scale) a. Camera sled b. Argo c. Side-looking deep tow d. Sea Mark
5. Near Bottom Geophysics a. Gravity b. Magnetics c. Deep-tow seismic array	6. Detailed Mapping a. Manned submersible b. Argo-Jason (ROV)
7. Micro seismic study	8. Background sampling (dredging, submersible, Jason) and sample analysis for compositional and structureal features

seismic studies to refine the structure between the holes.

E. What are the magnetic sources for magnetic anomalies? What is the average magnetic intensity and thickness of the different crustal layers? When was the magnetism acquired? What is the effect of fluid-rock interaction and faulting/mylonitization on magnetism? What is the effect of amagmatic extension (rotation, stretching) on magnetic anomalies. We need high resolution borehole magnetic data combined with careful magnetic studies of drill core samples through continuous vertical sections of oceanic crust to address this problem. In this way we can understand the average magnetic properties of a given crustal section, as well as the expected range of variation. These types of studies will allow us to better understand and interpret magnetic anomalies associated with crustal formation.

Drilling Strategy: Scientific Considerations

Four considerations are of primary importance to the structural community when sites for deep crustal/upper mantle drilling are to be selected. These are:

1. The ability to correlate structures in the extracted core with seismic velocity discontinuities such as the Moho, the layer 2-3 transition zone, and the various dipping lower-crustal reflectors. These features are all important lithospheric architectural elements, the character of which is presently unknown (or at best very poorly known). A major question to be considered is whether it will be possible to drill most or all of these structures at the same site. If possible, this would seem to be a strong argument for essentially total crustal penetration.
2. The ability to link observations of the extracted core to active processes. Of particular interest here are determinations of magnitudes, orientations and styles of *in-situ* stress, seismic studies to determine magnitudes, focal depths and first-motion geometries, and the presence, pervasiveness and deformation-coupled effects of hydrothermal fluid flow.
3. The potential for drilling long, essentially continuous sections of fresh rock. This is important for many reasons such as laboratory determination of physical properties, study of deformation microstructural development, and investigation of pressure-temperature-time histories preserved in the deformed material;
4. An attempt should be made to span a range of tectonic environments. Candidates include transverse ridges, transform valleys, median valley faults, and other targets such as failed rifts and propagators.

Site Survey Requirements

A site survey for deep drilling should consist of sufficiently detailed studies to characterize potential drill sites in terms of geological and geophysical properties on scales from tens of kilometers to meters. Because of the large time commitment to a deep hole, special efforts must be made to establish the small-scale features of the site and to correlate the geology and geophysics of the site to the major features of the area. In order to insure maximum returns on the drilling effort more detailed studies are needed compared to most past site surveys. In Table I we list a suggested suite of studies and appropriate tools.

Most of the items listed above are commonly used for site surveys and require no special explanation. Items 4-6, however, have special importance for deformation studies of a deep crustal drill hole and core.

The intermediate-scale studies are needed to insure that the drill site will be located over basement outcrops whose local geological and geophysical context is well established. Especially in areas where deep crustal or upper mantle lithologies are exposed on the sea floor, steep slopes and active tectonic processes dominate. Steep outcrops are separated by relatively flat terraces and in many places by down-slope trending canyons. The terraces and canyons generally contain substantial accumulations of talus, rubble and breccia, often covered by a veneer of pelagic ooze. The drill site must be located away from these types of areas. In addition, special efforts must be made to rule out the possibility of drilling into a large, partially buried block of material that has fallen from higher up-slope.

Near-bottom geophysics can help target subsurface features and establish correlations between geophysical anomalies and geological features. These can provide important links to regional geophysical surveys.

The detailed sea floor surveys must also locate viable drill sites on an engineering scale. Attention must be given to such factors as slopes, rock type at outcrop, fracture density, representativeness of local deformation structures, etc.

Special Requirements

Oriented Cores

Oriented drill core enhances our ability to reconstruct and interpret crustal deformation and tectonism in three dimensions. Currently, drill core recovered by ODP is oriented only with respect to vertical. Efforts to combine paleomagnetic data with borehole magnetometer data to determine the azimuthal orientation are underway. However, while such efforts are our only means of orienting the core after the fact, they are plagued by uncertainties and assumptions about the paleomagnetic declination. It is preferable to try and recover drill core which is physically oriented with respect to azimuth. ODP currently has the ability to retrieve fully oriented sediment cores using the Easman-Whipstock multishot camera. A system similar to this is probably unreasonable for hard rock cores which rotate within the core liner. A preferable solution may be to physically scribe the cores during drilling. A strong recommendation from this panel is thus for the ODP engineering staff to work on this problem.

An additional way to orient cores may be to develop an optical imaging system for wire line use in the borehole. The borehole televiewer is very good at imaging features which are acoustically distinct such as fractures and breakouts. However, a means of identifying smaller scale features such as foliation and layering would be very useful in mapping the three dimensional structures with the drilled section. This could possibly be done with a wireline video camera.

Sampling and Handling

Current ODP policy for sampling and handling of drill core was designed with fine-grained lithologies in mind. Coarse grained samples such as gabbros and ultramafics require a more carefully thought out strategy. Specifically, sections of whole core should be preserved for physical property measurements. Routine cycling of minicore size sample through all of the shipboard laboratories may not adequately represent these coarse grained lithologies. Any special facilities for the handling of large amounts of hard rock samples, need to be acquired (e.g. grinders etc).

VII. Fluid-Rock Interaction Working Group

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Outstanding Problems

1. **What is the contribution of the lower oceanic crust and upper mantle to the global geochemical budget of the oceans?**
2. **What are the effects of fluid-rock interaction on the chemical and physical characteristics of the oceanic crust?**
3. **What are the spatial and temporal dimensions of lower crustal hydrothermal activity, and how are they coupled to magmatic and tectonic processes?**

Preamble and State of the Art

Crustal rifting involves deformation, metasomatism and partial melting of the earth's crust in response to the input of mantle-derived magma from below and seawater from the hydrosphere above. The ultimate outcome is the development of chemically and mineralogically layered oceanic crust. One important aspect of this global process is the circulation and reaction of seawater within and near the region of crustal accretion.

When magmas encounter water-rich rocks in rifting environments, hydrothermal activity redistributes mass and energy by the circulation of heated seawater. The thermal history of the intrusion and its host rocks are dramatically affected by these hydrothermal systems. Although the thermal, mechanical and chemical processes that characterize these systems are the same worldwide, each magma hydrothermal system is unique in that it operates within a volume of the earth's crust that is characterized by its own structures, stratigraphy and geologic history.

Alteration products formed by the hydrothermal system result from the interaction between interdependent physical and chemical processes. The emplacement of magma produces potential fields for deformation, fluid flow and chemical reaction. During cooling of the magmatic heat source, expansion of the rock and contraction of the magma generates differential stresses that enhance rock permeability. This, together with fluid buoyancy forces near the intrusion, leads to increased fluid flow and convective heat transfer. Seawater modified by continuous reaction with the oceanic crust is transferred by circulation across regions of contrasting physical-chemical environments, this disrupts local equilibrium and increases chemical affinity creating irreversible reactions that cause minerals to precipitate and fill fracture networks decreasing rock permeability. These interdependent processes modify the physical and chemical properties of the oceanic crust, producing complex compositional and paragenetic assemblages of secondary minerals and networks of fractures that record the geologic history of the system. It is our objective to use these mineralogic and structural patterns to interpret the hydrothermal evolution of oceanic crust.

Hydrothermal vents in zones of oceanic rifting are the sea floor expression of deeper magma-hydrothermal processes within oceanic crust. In the 12 years since they were first discovered, the geographic and structural distribution of these ocean floor hot springs has been well established. Analysis of the vent fluids as well as thermodynamic and transport modeling have elucidated the inevitable impact of these fluids on the shallow ocean crust. Much less is known about the consequences of high-temperature reactions on the deeper rocks of oceanic layer 3 and of the upper mantle; specifically what is the contribution of layer 3 to the thermal and chemical aspects of the vent fluids? Without information of this sort, we are seriously limited in any estimates of the bulk composition of the crust, especially its complement of volatile components such as water and chlorine.

Experimental studies of water-rock reactions and evidence from ophiolites suggest that the zone of highest-temperature reactions and most efficient extraction of metals lies in part within layer 3 rocks. The paucity of samples of these deeper crustal rocks precludes the investigation of thermal extraction and water-rock reactions that generate the hydrothermal fluids observed in submarine hot springs. The recovery of deep crustal rocks by drilling will permit the cumulative effects of hydrothermal processes on the thermal, mechanical and chemical evolution of the oceanic crust to be examined. This is the optimum strategy for studying the deeper and higher temperature portions of the sub-sea floor hydrothermal systems.

Outstanding Problems

1. What is the abyssal lower crust and upper mantle contribution to the oceanic global geochemical budget?

Man's fascination with the salt sea is reflected in folklore and in scientific investigation: why is it salty, and how is this maintained? Until 25-30 years ago, ocean chemistry flux calculations considered only river input of elements, and element removal by authigenic sedimentation and entrapment in pore water. Two discoveries, however, have radically changed the way the processes controlling seawater composition are viewed. First is the advent and acceptance of plate tectonics - which entails continuous creation of crust at ocean ridges and its destruction at trenches. The second is the discovery of submarine hot springs, where seawater is discharged with severely modified composition due to interaction with newly formed crust. The result of this is that the ocean crust itself is now regarded as a major elemental source and sink for seawater, and that the chemical communication between mantle and crust includes a dynamic two way process of seawater hydrothermalism.

Reactions giving rise to hot vent fluids are thought to occur in relatively shallow circulation systems driven by a magmatic heat source. The base of the circulation is believed to be at the top of an axial magma chamber located about 2 km below sea floor. These systems have been reasonably well defined through sampling of vent fluids and upper crust, and by experiments and theoretical modelling. Key questions remain, however, about the deep portions of these axial hydrothermal systems and involvement of underlying layer 3 gabbros and mantle. The "reaction zone" located near the top of the magma chamber has yet to be sampled from oceanic crust. In ophiolites, up flow zones are represented by epidosites - quartz-epidote rocks - at the base of sheeted dykes or the layer 2-3 transition zones. Significant chemical exchange occurs in these zones, which may affect the composition of the vent fluids. Moreover, these zones are a possible source for metals for the vent fluids and hydrothermal deposits on the sea floor. The sampling of these reaction zones is an important part of understanding the deep portion of axial hydrothermal systems and the resulting chemical fluxes between the seawater and the crust. A second key question is whether and how the layer 3 gabbros and uppermost mantle are linked to these axial hydrothermal systems. Do magmatic volatiles get incorporated into hydrothermal fluids? Is there deep fluid circulation along the sides of the magma chamber? Do these fluids contribute toward the shallow axial hydrothermal system?

Another important source of mass transfer is the off-ridge hydrothermal circulation. According to heat flow estimates, between 60 to 90% of the convective heat loss from ocean crust occurs off ridge axis. Depending on the permeability structure of young oceanic crust, off-axis circulation could be deep (layer 3 gabbros) and contribute significantly toward mass transfer between seawater and oceanic crust. Penetration of seawater into uppermost mantle along deep faults at spreading centers and at fractures zones may also contribute to chemical fluxes. Hence, samples of layer 3 gabbros and uppermost mantle are essential to understand and quantify the fluxes due to seawater-crust interaction.

The resulting changes in chemical and mineralogic makeup of the crust are equally important to quantify because the altered crust is cycled back into the mantle at subduction zones. The behavior of secondary minerals during subduction may play a role in the genesis of arc magmatism. The cycling of altered crust into mantle may contribute to mantle heterogeneities. Any meaningful investigation of crust-mantle cycling is predicated on how well we know the composition and mineralogy of the altered crust. Our current knowledge of layer 3 composition cannot be improved or quantified without drilled samples.

2. What is the effect of fluid-rock interaction on the physical-chemical character of the oceanic crust?

Detailed studies of hydrothermal systems at mid-ocean ridge spreading centers have established that fluid-rock interactions have a profound effect on the chemical composition, mineralogy and isotopic ratios of the upper oceanic crust. An important goal of future oceanographic research is to assess the nature and global significance of hydrothermal alteration and chemical mass transfer in the lower oceanic crust and upper mantle. Preliminary studies of drill core of ocean layer 3 recovered from the Atlantis II transform (Hole 735B) indicate that fluid-rock interactions in the lower oceanic crust are initiated at extremely high temperatures (>600°C). Further studies of ocean layer 3 and the upper mantle are required to determine the contribution of components derived from deep level rock to the vent fluids at mid-ocean ridge hot springs. The subsolidus fluid history is recorded by hydrothermal veins, secondary mineral assemblages, and fluid inclusions that can only be understood through studies of continuous, unweathered samples from the lower ocean crust and upper mantle.

The passage of fluids through the ocean crust during and after its formation has a significant impact on its physical properties. Some of these properties, particularly density, temperature, elastic, electric and magnetic properties, can affect geophysical measurements made at the surface. A better understanding of the effects of alteration on physical properties may thus allow us to use surface measurements to extend our knowledge of the lower crust beyond the immediate vicinity of the hole.

Alteration may be observable seismically in several ways. The most obvious is the change in the gross velocity structure with time due to changes in mineralogy and porosity. Alteration in narrow regions such as shear zones may create impedance contrasts detectable by multi-channel seismic reflection studies. Alteration may affect the rheology of fault zones and hence their associated seismicity. Finally, the origin of the reflection Moho is unclear and may, in fact, be related to alteration.

Hydrothermal alteration can be expected to have a profound affect on the magnetic properties of the lower crust, and hence the associated magnetic anomaly. The magnetization of the gabbro layer and the mantle may be largely controlled by alteration. Depending on the nature of alteration, magnetization can be increased by the formation of magnetic oxides or decreased by their replacement. As remanence acquisition may be controlled by the timing of alteration rather than emplacement, the geometry of the source layer may be affected as well as the intensity.

The density of the crust influences its gravity signature. Alteration may increase density by filling voids or decrease it by replacing primary silicates with low density hydrous phases. The effect will probably be most pronounced in the case of serpentinization of ultramafics but may also be appreciable with mafics as well.

The temperature structure of the crust is strongly influenced by fluid circulation which can either bring cold water from the surface or heated water from depth. The temperature structure is reflected directly in surface heat flow and indirectly in bathymetry and gravity. It also has a strong influence on the cooling of the magma chamber and will have a major influence on magma chamber processes and the differentiation of primary magmas.

Alteration also influences the electrical properties of the crust both by changes in mineralogy and by the affect of fluid circulation on fluid composition and porosity. Larger scale electrical structure is, at least in principle, determinable by surface measurements.

3. What is the spatial-temporal dimension of hydrothermal activity in the lower crust, and how is it coupled to magmatic-tectonic processes?

The spatial and temporal dimensions of alteration reflect the evolution of the permeability structure of the oceanic crust. A complex interrelationship exists between permeability and the magmatic and tectonic processes occurring in the vicinity of ridge crests. Permeability and thermal structure determine patterns of fluid circulation and alteration, all of which change with time. The lateral variability is a function of factors such as spreading rate, relative position within a ridge segment, and age.

The rate of change of permeability is influenced by the reactivity of the circulating fluids with the rock. This is reflected in precipitation sequences and secondary mineral assemblages. These assemblages, together with other data such as fluid inclusions, record changing conditions of temperature, fluid composition, and pressure.

Patterns of fluid circulation within a block of crust will vary both on short and long time scales. Vigorous high temperature fluid circulation occurs at ridge crests in zero-age crust. The depth to which the circulation cell extends is intimately coupled to magmatic processes since convection dissipates significant amounts of heat. Currently this depth is unknown. Patterns of alteration should reflect the early history of fluid circulation and yield insight into the depth of the reaction zone feeding black smokers, e.g., whether it is restricted to layer 2, or whether, and how far, it extends into layer 3. It is important to assess, within this time frame, the relative contribution of mass flux from layer 3, the residence time of seawater-derived fluids in the lower crust, and whether fluid circulation in the lower crust is intimately linked to circulation in the upper crust. Likewise it is important to assess these same things in older crust, located further from the axis, as lower temperature circulation cells overprint earlier cells, and extend further into the crust and upper mantle.

The lateral and vertical scales of convective systems active in the lower oceanic crust are poorly defined. Sea floor heat flow measurements can help define dimensions of convective systems by determining down flow and up flow zones. We need to know if these are related to the scale of circulation in lower crust.

Vertical characterization of alteration in a borehole through layer 3, directly correlated to geophysical logs, should help identify whether reflectors mark alteration boundaries. If so, regional surveys could effectively map the vertical distribution of alteration type or intensity without the need to drill. This is the only cost effective way to get a regional picture of the spatial distribution of alteration in the lower oceanic crust.

Ophiolites are generally thought to be representative of modern ocean basins, but there are differences in their respective layer 3 petrographies. Before we utilize ophiolite models to understand the pattern of alteration in the lower oceanic crust, we need to establish how such petrographic differences would influence alteration.

Why Drill?

In order to investigate thoroughly the processes of fluid-rock interaction in the lower oceanic crust and upper mantle, it is essential to drill. This technique provides samples not overprinted by weathering: a major problem with most samples collected by dredge or submersible, especially ultramafic types.

Because of the heterogeneous distribution of alteration it is essential to have continuous core. This will provide an unbiased view of the proportion of altered versus unaltered rocks as a function of depth. Dredge collections certainly contain an unknown amount of such bias, because sites exposed by tectonism produce talus ramps of material shed from fault faces which appears preferentially altered at retrograde conditions (usually greenschist or zeolite grade).

Drilling provides a snapshot of the distribution and orientation of cracks, veins, and shear zones, which provide pathways for fluid circulation. A reliable record of the distribution with depth of the importance of these features can be obtained only with continuous coring.

Drilling provides an opportunity to sample *in-situ* fluids at depth, although it is obviously true that the fluids which will be sampled are not necessarily those responsible for the majority of the reactions seen in the mineralogy of the rocks cored Other benefits of drilling include the ability to determine magnetic stratigraphy, to perform a wide array of logging experiments, and the option to establish long-term monitoring, time-series sampling of fluids, and *in-situ* experiments.

Information Needed

The information needed to answer the scientific questions posed above fall into three broad categories: information available from the core (rock samples), from fluid samples, and from *in-situ* measurements within the drill hole.

Petrological study will require modal analyses of rocks and veins, mineral chemistry (including stable and radiogenic isotopes) of the key alteration phases, bulk chemistry of both fresh and altered rocks (assuming that suitably large samples of coarse-grained rocks are made available for analysis), and fluid inclusion analyses. Such information will yield local details including: the amount of crust that is altered by various processes and to what degree; the distribution of alteration zones; the mechanisms and sources of fluid infiltration; and the geometry of fluid circulation. Combined with tectonic studies, the interplay between hydrothermal activity and deformation can be constrained, but will require physical and magnetic property measurements as well as structural (deformation) analyses of oriented samples. Detailed mineralogic, chemical and isotopic analyses of core materials are also critical for experimental and theoretical modeling of hydrothermal alteration processes at mid-ocean ridges and their flanks.

For drill holes sited in crust sufficiently young to have hydrothermal activity, down-hole properties (e.g. temperature, porosity, permeability, and resistivity) must be measured. In addition, chemical and magnetic logs, as well as complete televideo imaging with computer-controlled image processing technology must be done for all holes. Fluid compositions need to be analyzed where samples can be taken (obtainable through time-series sampling in suitable holes).

Any deep crustal drill hole must be located in a regional geological and geophysical framework, requiring that regional site surveys utilizing seismic, gravity, magnetic, and heat flow methods must be obtained first. The drill hole then will serve as "ground truth" for the regional surveys, and the drilling results will have much broader and more general significance.

Standard down-hole logging needs to be complemented by VSP, OSP and packer experiments, BHTV and large scale resistivity measurements made *in-situ*. Finally, the hole must also serve as a continuing natural laboratory, with long-term physical and chemical sensors to measure stress fields, microseismic activity, thermal, and chemical evolution.

Strategy

To satisfy a large proportion of the objectives associated with hydrothermal alteration of the lower crust, the first priority is to establish a clear view of the distribution and nature of alteration across the Layer 2-3 boundary, which we take here to be equivalent to the sheeted dike-gabbro transition. This would give crucial information towards all three of the major problems set out above, both through characterization of the solid materials involved and also through direct and indirect evidence about fluids.

We consider that two kinds of sites have equal and very high priority for this study. There are clear advantages in correlation with geophysical observations and in ensuring a representative sample of layer 3 if one of the sites samples the Layer 2-3 transition beneath a normal sequence of extrusives and sheeted dykes, well away from fracture zones or other areas of tectonic disturbance. The existence of Hole 504B, already drilled most of the way to this target, gives a fine opportunity for reaching this goal. We therefore propose deepening Hole 504B to pass the Layer 2-3 transition, and to penetrate substantially beyond that into layer 3. We do not press (at present) for Hole 504B to be deepened towards Moho depths, though we anticipate that this may be a viable and welcome future possibility.

To complement this drilling we seek a parallel site in which the Layer 2-3 boundary is exposed at the sea floor. Such exposure implies large-scale tectonic unroofing, so that sites of this kind may be regarded as in some way anomalous. However, areas of exposed Layer 2-3 boundary will allow multiple penetration of the boundary and the underlying gabbros to investigate space-time relationships in alteration. In ophiolites the Layer 2-3 transition is spatially extremely variable, even on a scale of hundreds of meters, so that multiple penetration in at least one area is necessary if it is to be properly characterized. Areas with the necessary sea floor outcropping of the transition are known at the Vema Fracture Zone in the Atlantic, and the transition may outcrop in the vicinity of Hole 735B in the SW Indian Ocean or near the Kane Fracture Zone.

An additional consideration in selecting a drill hole site is the spreading rate of the crust, as there are predictable differences between the hydrothermal alteration of the lower crust related to variations in tectonic and magmatic processes. The fracture zone sites suggested above expose slow-spread crust, and Site 504B is situated on intermediate crust. Exposures of the lower portions of fast-spread crust are rare. The tectonics of ridge abandonment, however, may provide the opportunity to drill fast-spread oceanic crust and mantle. The Mathematician Ridge is an example of such a failed rift in fast-spread Pacific ocean crust which exposes layer 3 near the top of ridge parallel escarpments.

We recommend that site surveys should fully characterize one of these areas as possessing a Layer 2-3 boundary exposed over several kilometers, and that sites should be chosen for drilling to include a variety of alteration characteristics. At least one of the holes should penetrate a fossil zone of high temperature hydrothermal alteration, and some spatial association with an extinct black smoker system would be an advantage. We recommend one deep hole through the Layer 2-3 boundary to penetrate 1 kilometer into layer 3, and 3-4 single bit holes sited relative to the deep hole to give the extended spatial coverage.

The second major thrust of our program would be the drilling of an extended hole in the plutonic section. A continuous, extended section of plutonics, hopefully more than 2 km long, would be most important in establishing the fluxes from and into the plutonic layer, the nature of the transformed solid materials and the large and small-scale spatial variability of the plutonics. A second goal would be another site placed 2-5 km away to assess lateral variability in deformation, major shear zones, extent and similarity of metamorphism. The two sites could be at variable distances from major faults. We suggest that such sites could only be feasible in sections that could be rapidly drilled (e.g., gabbro). We envisage two possible areas for such an extended section(s), and would hope eventually that both could be drilled. One type of area would be that proposed for the detailed study of the Layer 2-3 transition. In areas such as the Vema Fracture Zone, it would be possible to offset from the Layer 2-3 transition to deeper structural levels, and begin a deep plutonic penetration there. Such a site might eventually penetrate the Moho, but even if it did not do so, the returns from such a single extended section would be great. It is important to emphasize that long plutonic cores must be "anchored" either at the top or the bottom to the transitional zones (layer 2-3 or layer 3/4), as a practical solution to not having continuous core from layer 2 to layer 4. A long core in plutonic rocks that is not anchored, that is, not well located in the oceanic stratigraphy, is less useful.

There would be great value in a extended section from an area of plutonics not associated with a transform fault. Since we do not see this as a possibility at Site 504B yet, we recommend that such a site should be sought either in an extinct ridge setting (such as the Mathematician Ridge) or in some other non-transform environment where plutonic rocks are exposed near the sea floor. An extended section from such an area would be strongly complementary to one from a near-transform environment, investigating at a primary level whether the transform environment is representative of other plutonic areas of crust.

The geophysical Moho is a boundary the significance of which is at present unclear. It is of great importance to know whether it corresponds to a primary lithological transition or to an alteration boundary. If the Moho corresponds to a transition between mafic and ultramafic rocks, there will be a marked change in the nature of alteration because of the very different chemical environments between the two units. If it corresponds to an alteration boundary between more or less serpentinised peridotite, then that too has importance in alteration, especially in determining whether serpentinization limits downward penetration of hydrothermal circulation, as has been previously suggested.

Reaching the Moho through a complete crustal section will very likely not be feasible in the near future. Although we are conscious that tectonically elevated occurrences of the Moho are likely to be in one way or another anomalous, we recommend that drilling should be undertaken at one such site to begin characterization of the Moho. There are some sites (Vema Fracture Zone, Atlantis II Fracture Zone) where geophysical evidence exists that the Moho may lie not too far below present exposures of gabbroic plutonics. Other sites may be discovered in diapiric settings, but tectonic disturbance is likely to be greater there.

Site Surveys and Special Needs

The most exacting site surveys would be required in the transform fault sites. There the site surveys would not only have to establish the position of the Layer 2-3 boundary over a length of at least 5-10 kilometers, but also would need to characterize the nature of that boundary and the relationship with extinct high-temperature hydrothermal systems. This will require intensive surveying by submersible or by other visual means, resulting eventually in identification of individual bare-rock sites of rubble-free unfractured outcrop. Initial investigations have already been completed in the Blanco Trough and Vema Fracture Zone, but a substantial amount of future survey effort is clearly required.

Site 504B requires no further site survey for the objective proposed here. The Mathematician Ridge area, which we identified as appropriate in two sections above, does however require more survey to prove its suitability and identify specific targets. There, the relationships between the plutonics and the surrounding rocks have yet to be fully defined. It would also be important to understand more clearly the processes by which the plutonic rocks come to be exposed at the sea floor.

Site surveys at all sites should include a thorough local to regional geophysical study to provide a framework within which the plutonics can be related to the structure of the surrounding crust. It may be necessary to link this work with the scale of drilling via very small-scale geophysical experiments in the vicinity of the drill sites to determine physical properties on the scale of hundreds of meters.

Alteration studies require intensive in-hole investigations after drilling is complete. These must include measurement of the crustal permeability, mapping fracture systems in the hole using a borehole televiewer, and collection of fluid samples wherever possible. A full suite of logs must be run, including chemical and magnetic logging tools. Sufficient time has to be made available after drilling for these important in-hole objectives to be met.

VIII. Crustal Architecture and Seismic Stratigraphy Working Group

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State of the Art

Due to the technological limitations of drilling in the past, most of the models of the ocean crust have largely been based on geophysical data, sampling and observations of exposed oceanic crust, and analogies with ophiolites. Although geophysical techniques such as seismic reflection and refraction have given us first order knowledge of the crustal architecture, we still have little direct knowledge of the structure, composition and physical properties of the deep oceanic crust. Deep crustal drilling is essential for uniquely determining the bulk composition and physical properties of the oceanic crust, which in turn give geological significance to the presence of seismic reflectors, seismically defined crustal layering, and the source of magnetic anomalies.

Although the concept of crustal architecture encompasses the lithological, compositional, and physical properties of oceanic crust, we have concentrated our discussion on the aspects of deep drilling that can directly address and resolve models based on geophysical and structural data.

Seismic investigations of the oceanic crust have progressed from imaging the sedimentary section and basement to total crustal imaging since the mid-seventies. The routine imaging of Moho and increased resolution of intracrustal reflectors now allows an evaluation of normal oceanic crustal structure and its variability to be made throughout the ocean basins. Our ability to characterize seismic crustal structure in various tectonic environments has revealed a level of complexity in structure which invalidates the layer cake model of crustal structure popular in the seventies.

The petrologically defined isovelocity layers of the layer cake model have been replaced by a model of the crust in which velocity gradients are the rule rather than the exception, and where the layer boundaries, if they exist as discrete entities, are defined by changing velocity gradients. As well as redefining the vertical structure of the crust, the seismic method has also revealed intriguing sub-horizontal reflectors within the crust at certain localities, which may be interpreted as (listric) fault zones. Significantly, these reflections appear on profiles obtained both parallel to and perpendicular to spreading direction.

Measurement of the magnetic signature of the oceanic crust has not experienced any technological breakthroughs; however, investigations of the amplitude and phase variations of the signal, spectral characteristics, and detailed rock magnetic studies have inferred the existence of sources of the anomaly pattern that are deeper than the upper crust, as well as identified the importance of secondary magnetizations as a potential carrier of the magnetic signal. Characterization of the magnetic source layer by direct measurement in an *in-situ* continuous stratigraphic column will potentially resolve ambiguities in the interpretation of crustal magnetic anomalies and allow detailed interpretation of the second order variations in the signal in terms of crustal alteration, grain size variations and characteristics of the accretion process to be carried out.

The measurement of gravity has experienced an order of magnitude increase in resolution over the last decade owing to a new class of axially symmetric gravity meters. Gravity data is currently able to resolve density variations within topographic features whereas previously only large crustal structure variations could be confidently characterized in terms of their density contrast. Dense gravity surveys, in conjunction with high resolution seismic data can be used to map lateral variations in crustal structure once a density model is calibrated by *in-situ* borehole measurements. This method could possibly resolve undulations in the transition at the layer 2-3 boundary and the Moho.

Primary Objectives and Drilling Strategy

A primary objective in understanding oceanic crustal architecture is to determine the nature of its seismic and magnetic structure. On a gross scale this entails determining the proportions, distribution and lithologies in the crustal section and the careful investigation of lithologic transition zones. On a finer scale, it involves the correlation of the physical properties of individual samples (e.g. magnetic, elastic, density, porosity) with *in-situ* measurements of the physical properties of the crust (e.g. temperature, stress, resistivity). The final step would be to integrate the site-specific (down-hole) data with the local and regional data to develop a more accurate model for the structure of oceanic crust. This more realistic picture of the architecture of the crust will afford us a greater understanding of the interrelated magmatic, tectonic and hydrothermal processes involved in the formation of the oceanic crust and upper mantle.

In order to accomplish this, at least one deep hole that penetrates the complete crustal section and the Moho is required. Ideally this hole should be situated in a section of crust believed to be representative of a large volume of normal or "typical" oceanic crust. It is in these regions that the majority of modern surveys have been completed and appear to provide the most simple interpretations. At the present time, there is significantly less geophysical data from "abnormal" crustal sections and from regions bounding transform faults. Until such time that these areas can be adequately surveyed and are more completely understood, it seems unreasonable, from a crustal structural viewpoint, to invest the time and effort of a deep drill hole at these sites.

Although a deep drill hole would provide the most information regarding crustal architecture, a significant amount could be learned from intermediate-depth holes on slow and fast-spreading ridges or on tectonic "windows"; sections of the lower crust and uppermost mantle exposed on the sea floor (see below). Intermediate depth holes could be located to provide information regarding the temporal and spatial variation in magma chemistry, seismic continuity, ridge segmentation and magma chamber dynamics.

To test the ridge segmentation hypothesis (e.g. Macdonald et al., 1987) at least two intermediate holes must be drilled. One hole should be on the mid-section of a fast-spreading magmatic segment, the other at a ridge discontinuity. The holes could either be in zero-age crust or in crust up to 10 my old. Along slowly spreading ridges the crust adjacent to transform faults and smaller ridge-axis discontinuities may offer a window of opportunity to sample complete, composite crustal sections. Holes in tectonic windows should be designed to determine the nature of the layer 2-3 transition (dike-gabbro transition) and/or possibly the layer 3 - Moho transition.

Ridge-transform ("inside") corners typically are elevated, and available samples suggest that they commonly expose middle and lower crust. Ridge non-transform "outside" corners appear to contain an upper crustal section. Thus conjugate sites on the two sides of a ridge transform corner might provide a complete composite crustal section, initially formed at one location along the ridge axis. The fact of a common point of origin would allow assessment of geochemical mass balance for the entire crustal section. Paired holes as suggested above would also provide constraints on the tectonic processes by which ridge transform corners are uplifted and ridge non-transform corners maintain relatively normal elevations. However, before such drilling could be conducted, it will be necessary to better define the hypotheses for the ridge-transform, ridge non-transform asymmetry with geological and geophysical data.

Why Drill? (Geophysical Viewpoint)

Owing to the non-uniqueness of field inversion, magnetic (and gravity) anomalies cannot be used to deduce source magnetization (density) and thickness of the source layer(s) simultaneously; one of the two parameters has to be measured directly. Similarly, seismic measurements determine travel times and assumptions about the rock's physical properties enter the calculations before depths of reflectors are inferred. The seismic reflectors indicate a change in those properties (density, elastic parameters) not their absolute values.

Detailed heat flow models require knowledge of the parameters of thermal conductivity and permeability as well as the measurement of down-hole thermal profiles. Modeling the elastic behavior of the oceanic crust implies assumptions about rheological properties that need to be tested experimentally. Limitations for drill site selection result from the fact that magnetic anomalies disappear for north-south ridges near the equator (±20 degrees).

The recovery of an entire, not necessarily complete, succession from layer 2A to the shallow mantle from a location where seismic reflections, magnetic and gravity fields have been measured would mean a quantum leap forward in our understanding of the physical properties of the oceanic crust.

Potential Target Areas

(1) Total Crustal Penetration - the ultimate goal

A specific site for total crustal penetration cannot be rationally selected yet, because of: (1) the lack of the necessary seismic imaging at many prospective sites, (2) the wide range of possible scientific criteria for final site selection, and (3) limited experience with the new drilling technologies that may be required. High-resolution, deep-penetration seismic surveys need to be conducted at a number of prospective settings (e.g., EPR off-axis crust), to document the existence of the deep seismic horizons that may provide drilling targets. As the seismic data-base is increased, the various scientific criteria for selecting a site for total crustal penetration must be debated, e g.: rifted, slow-spreading crust vs non-rifted, fast-spreading crust; young crust in shallow water vs old crust in deep water; crust with 'normal' seismic structure vs thin crust; crust with high magnetic amplitude; the nature of structural segmentation of the spreading center, i.e., where to drill within a segment. As goals with intermediate crustal penetration are attempted first, the limits of the necessary technologies will become more apparent.

An example of a possible target which is already well-imaged seismically is the thick crust in the western North Atlantic; however, this is in deep water, and drilling to Moho would require drill-string lengths much greater than is presently feasible. Possible targets in young crust where Moho might be reached with the present drill-string presently lack adequate seismic surveys (e.g., the flank of the EPR) or need better-quality seismic imaging (e.g., 504B).

(2) Intermediate Crustal Penetration

There are two immediate possibilities for penetrating to the Layer 2-3 transition in 1-2 legs; both of these are holes that already penetrate Layer 2 basalts:

(1) Hole 504B in young, thin crust, if the hole can be reconditioned for deeper drilling.

(2) Hole 418A in old, thick crust in the western North Atlantic.

Another immediate possibility involves the penetration of crustal reflectors thought to be the expression of faulting. Many of those imaged in the western North Atlantic reach very shallow levels of the crust and may crop out at the base of the sediment column. Potentially comparable events have recently been imaged in the MARK axial valley. Many of these events represent targets that could be reached within the constraints of present drilling technology, and several should be attempted.

(3) Tectonic Windows

It is likely that important transitions, like the Layer 2 and 3 or the crust and mantle, can be reached in tectonic windows at fracture zones or at features like Hess Deep. Before such sites are selected, regional and fine-scale geophysical surveys are required, to document the the transitions, their relationship to regional geophysical horizons, and the effect of tectonic processes on the crustal structure.

Site Survey Requirements

The site survey requirements and selection criteria for "total crustal drilling" and "tectonic windows" were discussed in the COSOD II report. Any drilling objective should be selected after exhaustive geophysical surveys have been completed. It is important that "state of the art" seismic data (reflection and to a lesser extent refraction data) be collected at any possible candidate drilling site. The crustal structure at and near drill sites should be determined with the goal of understanding the tectonic setting. This would be especially important for "tectonic window" sites which may have complicated histories. Tectonic window sites also require detailed surficial mapping and sampling to characterize the areal petrologic and geochemical diversity. Site survey work needs to be undertaken immediately to gain a better understanding seismic structure and deep crustal reflectors. With respect to the characterization of the magnetic source layer, high latitude sites would be more informative than equatorial sites.

It is important to note that all deep crustal drilling requires multiple legs at individual sites or in the same area. Reoccupation of drill sites must be easily accommodated within the drilling schedule on a period of 9 to 12 months. In this scheme, ship scheduling should be driven by thematic drilling objectives rather than regional interests.

Special Drilling Requirements

Technological development:

Drilling: need to overcome a number of problems such as drilling fractured rock; hole penetration limits; hole instability; low recovery rates (especially for layer 2).

Logging and Borehole instruments: logging equipment and borehole instrumentation for deep holes need to withstand high temperatures possibly exceeding 400°C. Slim line tools will be required for mining hole sizes. Refined methods for sidewall sampling, borehole fluid sampling are needed. More effective use of boreholes for long term monitoring and sea-floor experiments is needed and will mean re-entry capability is also a requirement.

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Appendix I

Drilling the Oceanic Lower Crust and Mantle
a workshop

Schedule

7 - 11 March 1989
at
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

Sponsored by
JOI-US Science Advisory Committee, International Lithosphere Program
Working Group on the Nature and Evolution of the Oceanic Lithosphere, and
W.M. Keck Geodynamics Program, Woods Hole Oceanographic Institution

Welcome to Woods Hole and the JOI/USSAC Workshop on Drilling the Oceanic Deep Crust and Shallow Mantle!

Rules of Engagement

We are pleased to have you come and hope that our time together will be scientifically challenging and fruitful. In this meeting we seek to bring together different groups of earth scientists to establish the principal problems and priorities for oceanic deep crustal drilling and to design a program for the next ten years. It is crucial that we arrive at a well-defined, coherent program, which enumerates specific objectives. For this purpose we have created specific thematic working groups who will have the charge of writing specific proposals to address key priorities. These working groups are tentative and can be expanded.

This is a participatory meeting. That means that the discussion periods are separate from the talks - and are the audience's opportunity to participate. The selection of speakers for this conference was to some degree arbitrary - a choice had to be made between including everyone, or having extensive discussion of the topics at hand. The projectionist has therefore been directed to turn the projector off at the end of 25 minutes so that the talks will not run into the discussion periods. Speakers are reminded that at the end of their talks, they no longer have the floor - it belongs to the moderator and the audience. **The moderator will run the discussions and direct questions to the speakers or other members of the audience as he or she deems appropriate.**

Ask Questions! Make didactic statements, outrageous assertions, impugn the intelligence of the geologic community, vivisect pet theories, broadcast ideas - for heaven's sake communicate! Couch potatoes are not welcome here.

There will be a report from the conference which will be sent to PCOM, relevant ocean drilling panels, and distributed to the community. We also plan to draft a **summary article** of the workshop for *EOS*. You are invited to submit comments and questions which we can draw from in compiling the report. We are making a recording of the meeting for reference.

The success of this workshop depends on everyone's contribution. Ocean drilling is a tad bit expensive, and it is important to sort the wheat from the chaff as fast as possible to arrive at a well-defined, coherent program. It is the goal of these meetings, therefore, to address the controversial issues and define the points of disagreement by encouraging free-wheeling and open communication. It is hoped that **graduate students** will join into the fray - since they are going to be doing most of the real work anyway.

Some Logistic Notes

- Please register with Janet Johnson so that we will have a complete roster of attendees. Copies of this revised list will be available Wednesday afternoon.
- The speaker abstracts are printed in blue and arranged alphabetically and the poster abstracts in orange for Tuesday evening, green for Wednesday evening and buff for Thursday evening, each arranged alphabetically. Late abstracts will be available Wednesday afternoon.
- No badge = no meals.
- Speakers, please deliver your slides to Jack Cook or Tom Kleindinst in the projection booth at the start of the session.
- Please clear the room after the Wednesday afternoon session so that it can be re-arranged for the buffet and poster session beginning at 7:00 pm. Those making poster presentations may set up beginning at 6:45 pm.
- Additional Workshop Information is in the pink section.

Henry J.B. Dick
Janet M. Johnson
Hartley Hoskins
Organizing Committee

Drilling the Oceanic Lower Crust and Mantle

A Workshop

Sponsored by:
JOI-US Science Advisory Committee, International Lithosphere Program
Working Group on the Nature and Evolution of the Oceanic Lithosphere, and
W.M. Keck Geodynamics Program, Woods Hole Oceanographic Institution

March 7 - 11, 1989
Woods Hole, Massachusetts

Tuesday, March 7, (Swope Center, Marine Biological Laboratory)

5:30-9:30 PM Registration in Swope Center, Lower Lobby
6:30-9:30 PM Reception for participants in Meigs Room. Refreshments and light food will be served.

Poster Session
SUB-SEA EXPLORATION SYSTEMS

6:30-9:30 PM Poster Session:
- D.G. Gallo & R.D. Ballard (WHOI): **Argo-Jason Imaging System**
- R. N. Anderson & D. Goldberg (L-DGO): **Down-hole logging**
- H. Paul Johnson and Janet E. Pariso (University of Washington): **Hard Rock Pogo Drill**
- G. M. Purdy (WHOI): **Seismic Mapping of the Uppermost Igneous Crust with a Deep-Towed Explosive Source (DETES)**

Wednesday, March 8, (Clark Laboratory 507)

7:00 Continental Breakfast (juice, pastries, coffee)
7:45 Opening Remarks - Henry J. B. Dick, Craig E. Dorman and David A. Ross

Symposium
ABYSSAL DEEP CRUST AND SHALLOW MANTLE STUDIES: IDENTIFYING THE KEY PROBLEMS

Moderators: John M. Sinton (morning) & P. J. Fox (afternoon)

8:00-8:25 I. S. McCallum, The University of Washington: **Variability of Crustal Magma Chambers: Evidence from layered intrusions and other sub-aerially exposed intrusions.**
8:25-8:45 Discussion
8:45-9:10 Bruce D. Marsh, Johns Hopkins University: **Magma Chamber Processes**
9:10-9:30 Discussion
9:30-9:55 John F. Casey, University of Houston: **Petrotectonics of Ophiolites: Current Knowledge of Magma Chambers and Their Relationship to the Mantle.**
9:55-10:15 Discussion

10:15-10:35 **Break**

10:35-11:00 Enrico Bonatti, Lamont Doherty Geological Observatory: **The Abyssal Mantle.**
11:00-11:20 Discussion
11:20-11:45 Kenneth C. Macdonald: University of California, Santa Barbara: **Some Questions Concerning Tectonic Versus Magmatic Versus Geochemical Segmentation of Mid-ocean Ridges**
11:45-12:05 Discussion

12:05-1:05 **Buffet Lunch** - Clark 507

Tour of the Deep Submergence Laboratory (Jason/Argo): David G. Gallo

1:05-1:30 G.M. Purdy: **Seismic Evidence for Lateral Heterogeneity in the Ocean Crust and Shallow Mantle.**
1:30-1:50 Discussion
1:50-2:15 Nikolas I. Christensen, Purdue University: **Deformation and Structure in the Deep Ocean Crust and Upper Mantle.**
2:15-2:35 Discussion
2:35-3:00 Johnson R. Cann, University of Newcastle upon Tyne: **Alteration of the Deep Ocean Crust and Upper Mantle: Templates for Hydrothermal Circulation.**
3:00-3:20 Discussion.

3:20-3:40 **Break**

3:40-4:05 William B. Seyfried, University of Minnesota: **Seawater and Rocks: Chemical Exchange in the Deep Ocean Crust and Shallow Mantle.**
4:05-4:25 Discussion
4:25-4:50 Sean C. Solomon, Massachusetts Institute of Technology: **Just How Do Ocean Ridges Vary? Characteristics and Population Statistics of Ocean Ridges.**
4:50-5:10 Discussion

5:10-6:30 Break, **Tour of the Deep Submergence Laboratorv (Argo/Jason):** David G. Gallo
6:30-8:30 Buffet Dinner (Clark fifth floor)

Poster Session (Contributed Papers)
THE DEEP OCEAN CRUST AND UPPER MANTLE: EVIDENCE FROM OPHIOLITES, OCEAN DRILLING, REMOTE SENSING, AND SEAFLOOR EXPLORATION

7:00-10:00 Poster Session,Clark fifth floor

J. C. Alt, (Washington University): **Petrology of Sulfides and Sulfur Contents of Oceanic Gabbros**

K. Becker (University of Miami), et al.: **Drilling Deep Into Young Oceanic Crust, Hole 504B, Costa Rica Rift**

Dennis K. Bird (Stanford University): **Subsolidus Alteration and Deformation of Layered Gabbros: East Greenland Tertiary Igneous Province**

P. Browning, S. Roberts and T. Alabaster (Cambridge University): **Extremely Rapid Compositional Gradients in Ultramafic Cumulates from the CY-4 Borehole, Troodos Ophiolite: Implications for Magma Chamber Processes**

Hugo Buser (Consultant): **Paleostructures, a Model for Primary Crustal Development**

J. A. Collins (Australian National University), T. M. Brocher (USGS) and G. M. Purdy (WHOI): **Mapping the Seismic Structure of the Upper Oceanic Crust: Implications from DSDP Site 504B, Panama Basin**

J. A. Collins (Australian National University), G. M. Purdy (WHOI), T. M. Brocher (USGS): **How far to Moho at 504B ?**

D. Elthon, S.E. Smith, D.K. Ross, and Y. Liang (University of Houston): **Petrological and Geochemical Problems of the Deep Oceanic Crust and Oceanic Magma Chambers: Evidence from Ophiolites and Basic Layered Intrusions**

D. Goldberg (L-DGO) and K. Becker (University of Miami): **Indicators of *In-Situ* Fracture Permeability in Oceanic Layer 3**

G. D. Harper, G. T. Norrell, R. J. Alexander (SUNY, Albany) and Charles Schlinger (University of Utah): **Oceanic Faults and Shear Zones in the Josephine Ophiolite**

Stephen D. Hurst and E. M. Moores (University of California, Davis): **Solea Graben - Troodos Ophiolite: Tectonic Thinning at a Ridge-Transform Fault Intersection**

P. Meyer (WHOI) and S. Bloomer (Boston University) and K. Ozawa (University of Tokyo): **Igneous Textures and Primary Mineralogy of Gabbros from Site 735C**

Peter J. Michael (University of Tulsa): **The Agent of High-Temperature, Hydrothermal Alteration in the Oceanic Crust: Modified Seawater or Exsolved Magmatic Water?**

D. K. Ross, D. Elthon, J. F. Casey (University of Houston): **Find-Scale Variations in Mineral Compositions of Massive Dunites from Blow Me Down Mtn., Bay of Islands Ophiolite**

Craig M. Schiffries (Carnegie Institution of Washington): **Hydrothermal Systems in Continental Layered Intrusions and Implications for the Lower Oceanic Crust**

Debra S. Stakes (University of South Carolina), David A. Vanko (Georgia State University), Mathilde Cannat (GIS Oceanologie et Geodynamique, Brest), Catherine Mevel (Universite Pierre et Marie Curie, Paris): **Fluid-Rock Interactions and the Metamorphic History of Layer Three of the S. W. Indian Ridge: ODP Site 735**

Stephen A. Swift, Ralph A. Stephen and Hartley Hoskins (WHOI): **A Vertical Seismic Profile in Layer 3, Atlantis II Fracture Zone, Southwest Indian Ridge**

P. Thy (NASA, Johnson Space Center) and Y. Dilek (University of California, Davis): **The Troodos Ophiolite and Implications for the Lower Oceanic Crust**

R. P. Von Herzen (WHOI) and J. Scott (USGS) : **Temperature Logging in Hole 735B: Preliminary Modeling**

Additional poster space available, please apply to Janet Johnson.

9:00-10:30 Kegger

Thursday, March 9, (Clark Laboratory 507)

7:30 Continental Breakfast (juice, pastries, coffee)

Symposium
CHOOSING TARGETS AND DRILLING THEM
Moderator: Paul T. Robinson

8:00-8:25 Steven Howard (Ocean Drilling Project, Texas A&M University): **The Technology of Deep Crustal Drilling.**

8:25-8:40 Discussion

8:40-9:05 James Natland (Scripps Institution of Oceanography): **Between a Rock and a Hard Place: The Realities of Ocean Drilling.**

9:05-9:20 Discussion

9:20-9:45 Henry J.B. Dick (WHOI): **Opportunities and Drilling Strategies for Understanding the Deep Ocean Crust and Shallow Mantle**

9:45-10:00 Discussion

10:00-10:20 **Break**

Panel Discussions
THE PRIORITIES FOR DEEP CRUSTAL DRILLING
Moderator: Stanley R. Hart

10:20-10:40 Johnson R. Cann, COSOD II Steering Committee: **COSOD II Recommendations for Deep Crustal and Shallow Mantle Drilling.**

10:40-11:00 Peter J. Michael, Donald W. Forsyth, and Henry J. B. Dick: **Mantle Drilling.**

11:00-11:20 Discussion

11:20-11:40 Rodey Batiza, Stearns A. Morse, and Michael P. Ryan: **Igneous Petrogenesis**

11:40-12:00 Discussion

12:00-1:00 Buffet Lunch, Clark Laboratory
Steering Committee Meeting to make working group assignments

1:00-1:20 Steve Kirby, Gregory D. Harper, and David G. Gallo: **Ridge Tectonics and Rock Deformation.**

1:20-1:40 Discussion

1:40-2:00 Geoffrey Thompson, Debra S. Stakes, and Dennis K. Bird: **Hydrothermal Circulation and Rock Alteration.**

2:00-2:20 Discussion

2:20-2:40 S.A. Morse and Friends: **Discussion of 735B Core**

Planning Session
DOWN TO BRASS TACKS
Moderator: Henry J. B. Dick

2:40-3:00 Moderator, **Creation of Thematic Working Groups**
3:00-6:00 First Meeting of Working Groups
Tour of the Deep Submergence Laboratory (Argo/Jason): David G. Gallo

7:30-8:30 Dinner - Swope Center Dining Room, Marine Biological Laboratorys

Poster Session
SUGGESTIONS FOR DEEP CRUSTAL AND SHALLOW MANTLE DRILLING

7:00-10:30 Poster and Keg Session, Swope Center:
Jeffrey C. Alt (Washington University): **DSDP Hole 418B as a site for Deep Crustal Drilling**
Keir Becker (University of Miami): **Where to drill complete crustal sections??**
R. S. Detrick and E. Morris (University of Rhode Island): **Intracrustal Reflectors in Mesozoic-Aged Crust in the Western North Atlantic: a Target for Deep Crustal Drilling**
H. J. B. Dick and D. G. Gallo (WHOI): **Pop Up Tectonics and the Formation of Transverse Ridges:**
a Tectonic Model for the Evolution of a Half Kilometer Section of Layer 3 Drilled Near the Atlantis II Fracture Zone
Rachel M. Haymon (University of California, Santa Barbara) and Randolph A. Koski (USGS): **Hydothermal Discharge Zones in the Oman Ophiolite and the Geometry of Hydrothermal Circulation at Oceanic Spreading Centers**
Jeffrey A. Karson (Duke University): **Drilling Escarpments on the Mid-Atlantic Ridge: Composite Sections Through the Oceanic Crust?**
David A. Vanko (Georgia State University) and Debra S. Stakes (University of South Carolina): **The Mathematician Fail Rift: Exposures of East Pacific Layer Three for Deep Crustal Drilling**
Additional poster space available, please apply to Janet Johnson.
9:00-10:30 Kegger, Swope Center, Lower Level

Friday, March 10, (Clark Laboratory 507)
7:30 Continental Breakfast (juice, pastries, coffee)

Planning Sessions
8:00-9:00 ***First Report of Working Groups***
9:00-12:30 **Meeting of Thematic Working Groups**

12:30-1:30 **Buffet Lunch**, Clark Laboratory
Tour of the Deep Submergence Laboratory (Argo/Jason): David G. Gallo

1:30-4:00 **Meeting of Thematic Working Groups**
4:00-5:30 **Final Report of Working Groups**
5:30 - ? Beer and Oysters

1:30-4:00 **Meeting and Writing session for working groups**
4:00-5:30 **Final report of working groups**, Formation of working groups to produce specific drilling proposals. Discussion of need for a permanent deep crustal and shallow mantle working group in the JOIDES planning structure.
Discussion and Counterpoints - Contributed by Participants at Meeting.
5:30 - whenever - Beer and Shellfish, End of general meeting

Saturday, March 11, (Clark Laboratory 507)
8:30 Continental Breakfast
9:00-12:00 **Steering Committee Meeting**: Discussion of Meeting

Speaker Abstracts

Alteration of the deep ocean crust and upper mantle: templates for hydrothermal circulation

Joe Cann, University of Newcastle upon Tyne

Hydrothermal alteration is apparently widespread in the lower ocean crust. Evidence from ophiolites suggests that the most intense alteration is in the lower part of the sheeted dyke complex and the upper part of the plutonics. These hydrothermal reaction zones can be identified, characterized by the presence of epidosites (epidote-quartz rocks), depleted in Cn, Zn and Mn, with abundant high temperature fluid inclusions. Deeper levels of ophiolitic plutonics show lower degrees of alteration. Dredged gabbros from the ocean crust show a complete spectrum of alteration facies, ranging from late magmatic brown hornblende replacing pyroene, through amphibolite and greenschist alteration to zeolitic replacement of plagioclase. Such alteration is accompanied by variably intense cataclasis and mylonitisation, which can be shown texturally to be an early high-temperature event. Altered rocks of this kind probably represent products of fluid movement along fault zones - either ridge-crest parallel or transform faults - with the successively lower temperature facies being superimposed on earlier facies as the rock is cooled by circulating water. The plutonic section penetrated by Hole 735B shows less of this style of alteration than is represented by dredged samples, suggesting that the hole penetrated a fault block and the dredged rocks are recovered mostly from fault planes bounding such blocks.

The role of the lower ocean crust in hydrothermal circulation is not clear. Is magma the main source of heat for black smoker systems, or do these draw heat (and metals?) from solid plutonics as well? Is the lower limit of hydrothermal circulation defined by serpentinisation and swelling of the uppermost mantle, or by closure of cracks with depth in gabbros? What is the permeability structure of the plutonic section?

It is important to ask whether the pattern of alternation and deformation is different between ocean crust and ophiolites. Is the abundant cataclasis and alteration of ocean crust gabbros a function of their source environment or a fundamental difference?

Is ocean crust near fracture zones, from which most plutonic samples are recovered, anomalous in its plutonic history compared to ocean crust away from fracture zones? Is there a relation between alteration and tectonic factors such as spreading rate or degree of rifting of the crust?

Drilling has a large number of techniques suitable for answering these questions, both based on observations of core and on downhole logging and experiments. A simple drilling strategy can be evolved to obtain the most effective scientific return from a relatively small number of holes.

DEFORMATION AND STRUCTURE IN THE DEEP OCEAN CRUST AND UPPER MANTLE

Nikolas I. Christensen
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The composition and structure of the lower oceanic crust and upper mantle are still largely inferred from geophysical measurements, relying particularly on seismic studies. In many regions of the upper mantle seismic anisotropy has been revealed by its various signatures, including azimuthal variations in compressional wave velocities and splitting of shear waves. In 1964 Harry Hess first proposed that velocities are generally high perpendicular to ridge crests in the Mendocino and Maui areas of the northwest Pacific. More recent detailed refraction studies have clearly demonstrated that seismic anisotropy is a common phenomenon in the oceanic upper mantle. Studies of the seismic properties of ophiolites show that there is a strong connection in upper mantle peridotites between plastic flow, mineral preferred orientations and seismic anisotropy. Olivine and orthopyroxene show clear and systematic patterns of preferred orientation, with olivine crystallographic a axes and orthopyroxene crystallographic c axes showing strong maxima subparallel to spreading directions in the oceanic upper mantle. Shear-wave splitting is predicted for all propagation directions within the upper mantle. In many regions, anisotropy has been induced by plastic strain. There is no direct relation between upper mantle anisotropy and stress. The tectonite fabric which characterizes the mantle passes upwards with no change in orientation into the layered gabbros and peridotites at the base of the crust. With the exception of gabbroic rocks within mylonite zones, lower oceanic crustal anisotropy is relatively small, even though deformation may be a common feature of layer 3. Anisotropy of seismic attenuation may in the future provide additional constraints on the nature and extent of oceanic lower crustal and upper mantle deformation.

Opportunities and Drilling Strategies for Understanding the Deep Ocean Crust and Shallow Mantle

Henry J.B. Dick
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The new segmentation models for the ocean crust provide a new basis for a focused program of deep crustal drilling over the next decade. Combined with the recent discovery that drilling of layer 3 is relatively easy, once reached, and that this can be done utilizing tectonically exposed deep ocean crust, we have a remarkable opportunity to design a coherent program to answer many of the major questions remaining about the evolution of the ocean crust. To do this we must utilize the simple strategy of stratigraphers - that is piece together the whole from many partial sections of crust. For this purpose, however, we will require careful site surveys, and an enhanced knowledge of the tectonic evolution of the ocean rift mountains.

The purpose of this meeting is to come up with a coherent 10 year drilling program, at the end of which we will have a rough idea of the composition of the lower ocean crust and shallow mantle. Given the immense variability associated with variations in spreading rate, and proximity to mantle hot spots combined with the lateral variability predicted by the new segmentation models for the ocean crust, this is an immense task requiring considerable thought. Thus, we cannot come up with a random list of people's favorite drilling targets, but rather a very systematically thought out program with a consensus to back it up. That's a very tall order for a meeting of 150 people. Figure that given the composition of the entire drilling program, that we will at most have 12 drilling legs to do this. If we commit time towards total penetrations of the ocean crust, that would leave us with at most 6 legs for drilling partial sections of the lower crust and mantle. Alternatively we could ask ODP to reduce the commitment to total penetrations in order to devote more time to partial sections. As I think through the problem of evaluating the complex 3-D structure of the ocean crust, I lean more and more towards drilling series of long (1000 m) offset holes, as is done in the study of layered intrusions. The value of a single isolated holes (2-D) in understanding the nature of the ocean crust is really pretty limited. Using the 735B model, we could drill roughly 2 1000 m holes in a single leg. A program which might succeed in giving us a good idea of the evolution of the ocean crust might be:

1. Two penetrations down to 2000-3000 meters in adjacent sections of crust, one of which exposes layer 3, the other layer 2 intact, as suggested by the COSOD II report at a fast spreading ridge = 6 legs (4 to do the basalt drilling, 2 to do the plutonic drilling).

2. One deep mantle hole in a wave cut platform exposing mantle (e.g. near Vema F.Z.) to evaluate shallow mantle stratigraphy to 2,000 m = 1 leg. (Note that 735B demonstrated that drilling plutonic rocks is an order of magnitude easier than drilling fractured, brittle basalt.)

3. One deep hole (1500-2000 m) and 3 offset 750 m holes in tectonically exposed layer 3 at end-member fast and slow spreading ridges to evaluate the range of variability of the crust and shallow mantle = 2 legs each for 4 legs. For example the Nova Canton Trough or the Mathematician Seamounts in the Pacific and the Atlantis Bank at the Atlantis II F.Z. or the SW Indian Ridge (Site 735B).

4. One neo-tectonics leg to drill plutonic exposures on the walls of the median valley at a slow spreading ridge far from and at a ridge transform intersection to determine the nature and variability of faulting along rift valleys. For example we

could drill one hole to 1000 m into the gabbro exposed on the rift valley wall at the Kane F.Z., and one hole down to a 1000 m at the leg 109 peridotite site located further away on the rift valley wall. These holes would have the added advantage of getting us into the lower crust at near zero age, and permit us to evaluate early on the drilling conditions there for the zero age crustal drilling program (a separate, but complementary, lithosphere program to this one).

For any program to become a reality, however, calls for a considerable degree of consensus among the participants of this meeting, and for their continued commitment to this program, long after this meeting has adjourned.

Some Questions Concerning Tectonic Versus Magmatic Versus Geochemical Segmentation of Mid-Ocean Ridges

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Abstract

1. Are axial magma chambers centrally fed with along-axis flow or are they fed by a relatively unorganized distribution of mantle heterogeneities with length scales of ~5 km?

2. How long do individual magmatic cells last ? How is this linked to the longevity of ridge axis discontinuities of orders 1, 2, 3 and 4?

3. If the multi-channel results of Detrick et al. (1987) are interpreted as documenting continuity of an axial magma chamber on length scales of 20-80 km, how can this be reconciled with trace element studies which indicate a much finer scale segmentation (e.g., Langmuir et al. 1986)?

4. Is the axial low velocity zone a chamber full of crystalline mush with only a thin lens of magma at the top or is it a ~3x3 km reservoir of magma?

5. Do the lineated Seasat gravity anomalies of the South Pacific reflect a sustained, time-averaged pattern of upper mantle convection--melt segregation--tectonic/magmatic segmentation?

6. How are the issues above affected by spreading rate?

7. Is drilling the best way to answer these questions?

MAGMA CHAMBER PROCESSES

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ABSTRACT

The mystery of producing strong compositional diversity among suites of comagmatic igneous rocks is investigated by considering the dynamic evolution of basaltic magma in a sheet-like chamber. A central conclusion is that inward-progressing crystallization produces strong viscosity and temperature gradients that promote convection only near the leading edge of the upper thermal boundary layer. Convection is apparently confined to an essentially isoviscous, isothermal region that hugs the downward-growing roof zone. Strong changes in viscosity with crystallization divide the upper and lower thermal boundary layers into regions of decreasing viscosity and crystallinity (N) called "rigid crust" ($N \geq 0.5$), "mush" ($0.5 \geq N \geq 0.25$), and "suspension" ($N \leq 0.25$). The strong increase in viscosity near the mush-suspension interface acts as a capture front that overtakes and traps slowly settling crystals. Initial phenocrysts mostly escape capture, but crystals nucleated and grown in the suspension zone can escape only if the capture front slows to a critical rate attainable only in bodies thicker that about 100 m. Escaping crystals are redistributed and sorted by convection driven by the advance of the capture front itself. Crystal-laden plumes traverse the central, hot core of the body and deposit partially resorbed and sorted crystals within the lower suspension zone. Convection is never vigorous but is part of an over-all intimate balance between roofward heat loss, rigid-crust growth, crystallization kinetics, and transport and sorting of sinking escaped crystals. There is a strong similarity between these processes and those producing both varves and saline pan deposits. It is clear that lavas, lava lakes, and sills are indeed examples of true magma chambers strongly exhibiting certain aspects of this over-all process. These aspects commonly also characterize the large mafic magmatic bodies. Because strong compositional changes in the residual melt occur largely outward (that is, at lower temperatures and higher crystallinities) of the capture front, which is immobile and mostly within rigid crust, the possible range in comagmatic compositions available for eruption anywhere within the active magma is very limited. This is in broad agreement with the compositional range observed in basaltic lava lakes, sills, and plutons like Skaergaard. The tuning of convection, crystallization kinetics, and phase equilibria in chambers of this type can produce a variety of textures and layering but not a diversity of compositions.

Just How Do Ocean Ridges Vary?: Characteristics and Population Statistics of Ocean Ridges*

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It is well known that many aspects of mid-ocean ridges - including topographic relief, segmentation characteristics, and the interplay between igneous and tectonic processes - are strong functions of local spreading rate. To provide background for discussions of drilling targets for ridge segments of various spreading rates, I present a summary of the distribution of cumulative ridge length by spreading rate. From a simplified global map of the major mid-ocean ridge axis segments [1] and a model for global plate motions [2], it is straightforward to calculate the length and average spreading rate for each segment. One useful overview of the results is given in Figure 1, which is essentially a histogram of cumulative ridge length within equal increments of half-spreading rate of 1 mm/yr. The total length of ridge segments is 55,000 km. Prominent peaks represent large cumulative lengths of ridges spreading at half rates near 8-9 (the modal peak), 12-14, 17-20, 33-38, and 85-86 mm/yr. These peaks are dominated by major ridge systems located near the equators of their respective Euler poles (respectively, the Southwest Indian Ridge, the northern Mid-Atlantic Ridge, the southern Mid-Atlantic Ridge, the West Chile Rise - Southeast Indian Ridge, and the south-central East Pacific Rise). It may be argued that, by this classification scheme, the most common type of spreading center is typified by the Southwest Indian Ridge. Alternative classification schemes are by rate of formation of new seafloor and by rate of formation of new crustal volume. When expressed as a histogram in half-rate increments of 1 mm/y, the modal peak for the rate of creation of new seafloor is that at 85-86 mm/yr. The total rate of formation of seafloor area is 3.0 km^2/yr. The analogous histogram for rate of formation of crustal volume, for a given rate-dependent model for average crustal thickness [3], accentuates the heights of the peaks at high spreading rates further. By these last two classifications, the spreading center most dominant for crustal igneous activity is the south-central East Pacific Rise.

References: [1] J.G. Sclater, B. Parsons, and C. Jaupart, *J. Geophys. Res., 86,* 11535, 1981; [2] J.B. Minster and T.H Jordan, *J. Geophys. Res., 83,* 5331, 1978; [3] I. Reid and H.R. Jackson, *Mar. Geophys. Res., 5,* 165, 1981.

* Title by H.J.B. Dick.

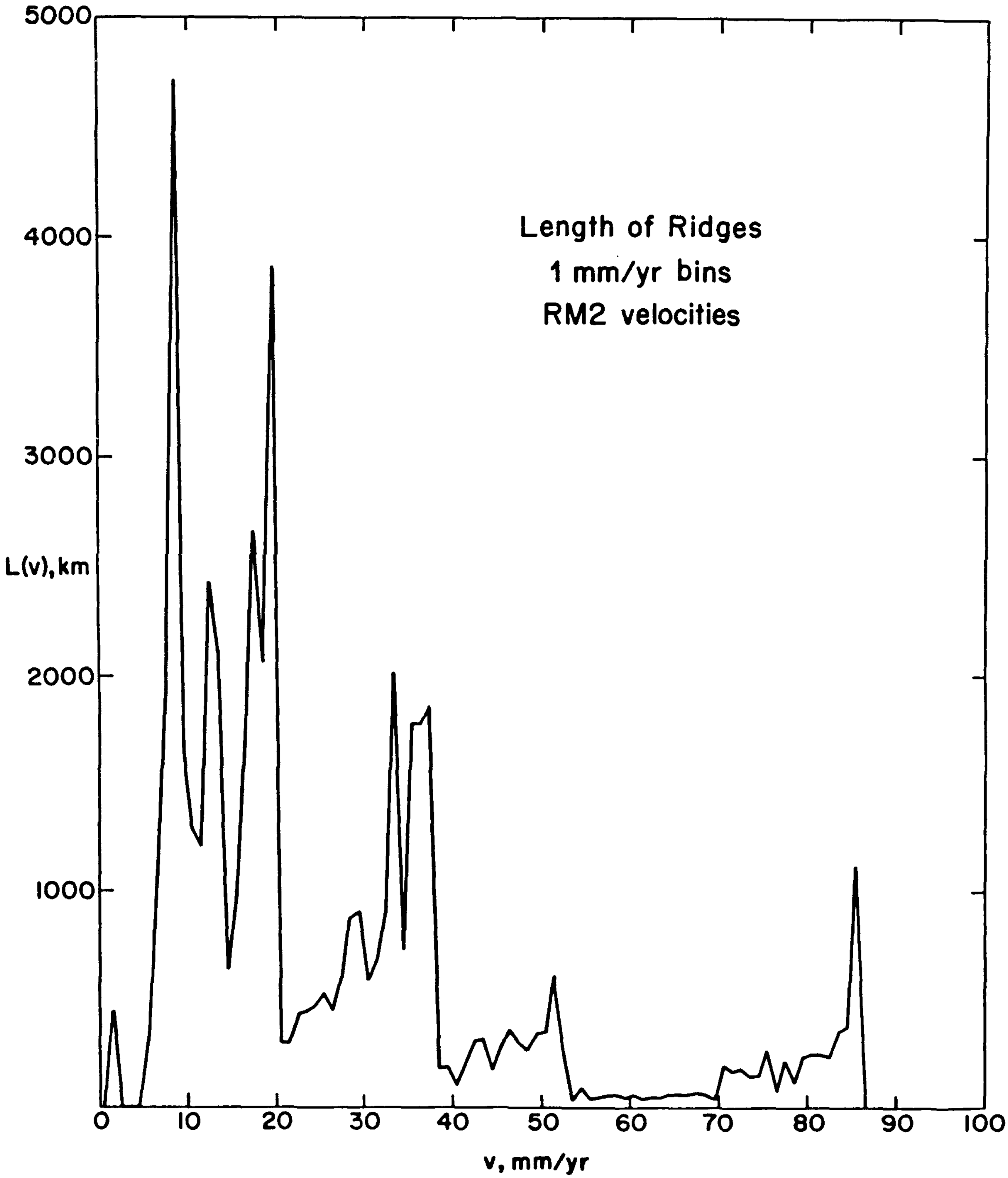

Length of Ridges
1 mm/yr bins
RM2 velocities
L(v), km
v, mm/yr
0
10
20
30
40
50
60
70
80
90
100
1000
2000
3000
4000
5000

Figure 1

ARGO/JASON IMAGING SYSTEM

David G. Gallo and Robert D. Ballard

The Argo/Jason seafloor imaging system was designed to provide the oceanographic community with an efficient means for real-time fine-scale (10's to 100's of meters) mapping of seafloor terrains. ARGO, a towed camera sled is designed to provide high-altitude (15-30 meters) wide area imaging (the bird's eye view) and incorporates a suite of SIT (Silicone Intensified Target) video, ESC (Electronic Still Camera), and side-looking sonar (100 KHz Klein) images. JASON is an ROV (Remotely Operated Vehicle) and is designed to be "terrain involved".

The JASON vehicle is equiped with multiple color video cameras (3), black and white video, color still cameras, and a high-resolution split-beam terrain mapping sonar (APL 200 KHz) capable of producing 300 meter wide swaths of bathymetric and reflectivity data. The JASON vehicle is equiped with a sampling arm and a sample basket. The ARGO vehicle contains a "sample drawer" capable of storing 1000 pounds of samples. The entire ARGO/JASON system is fiber optic and operates to a depth of 6000 meters

Hard Rock Pogo Drill

H. Paul Johnson and Janet E. Pariso (University of Washington):

Construction of a Deep-Sea Rock Drill

The University of Washington has recently been funded to design, construct, and test a deep-sea rock drill which will have the initial capability of penetrating and sampling igneous basement rocks, lithified sediments, and both sulfide and carbonate seafloor deposits to a coring depth of 3 meters. This drill will be deployable to depths of up to 5000 meters by a conventional research vessel, using the 'NSF-standard' 680 armored conducting cable. The drill will provide oriented rock cores from marine environments that are difficult, if not impossible, to sample using conventional sediment coring or dredging techniques. The ability to retrieve vertically oriented rock cores, from 10 feet below the surface of the sea-floor, opens a whole new vista of scientific opportunities. This capability will allow the research community to address problems that have previously only been approached using the DSPS/ODP drilling program.

For most marine geological and geochemical studies, the need for samples from the seafloor is paramount: further, the quality of the science that can be done from the samples is almost universally correlated to the quality of the initial sampling technique. As a general rule, oriented samples are more valuable than unoriented samples, and unaltered rock from the interior of the outcrop is more useful than altered surface samples. Until now, the marine geological community has been confined to the sparse resource of the drilling ship, the imperfect sampling capability of submersibles, or the lottery of a surface ship dredging program. The general availability of a working rock drill, which can be deployed from most vessels of the research fleet, should add substantially to our capability to sample the seafloor.

In addition to core samples, the drill holes generated within the seafloor should provide excellent sites for the placement of sub-surface instrumentation. These could include acoustic and seismic instruments which would be tightly coupled to basement (and away from water noise), temperature, permeability, porosity and potential field sensors, as well as tilt meters and other crustal strain gauges. The seafloor rock drill should be the logical intermediate tool between the inadequate sub-surface sampling and instrument-positioning capability of a submersible, and the limited availability of the JOIDES Resolution.

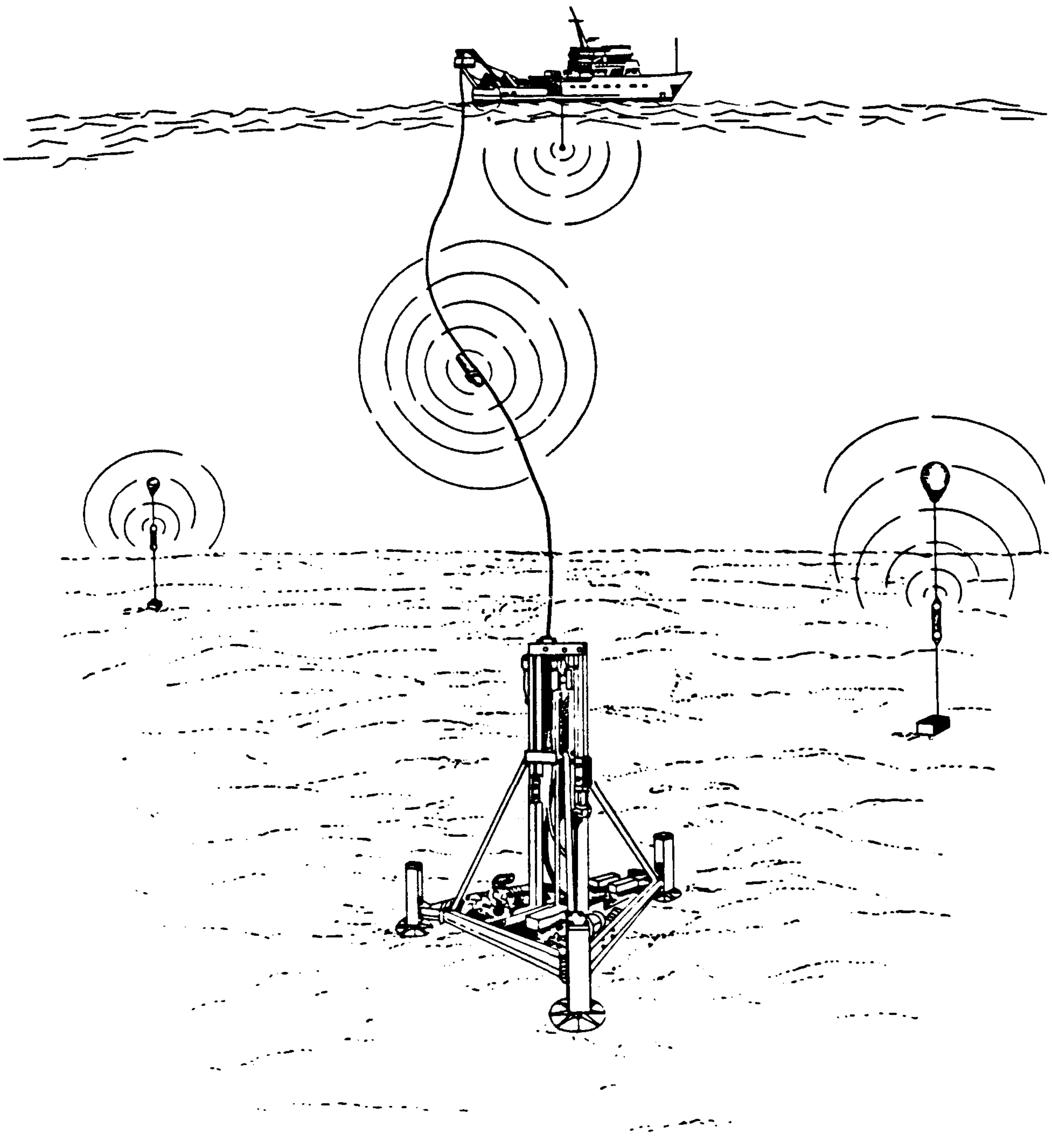
The construction of the UW rock drill, funded jointly by the National Science Foundation and the Office of Naval Research, is scheduled to begin in February, 1989. Additional funds, to convert the rock drill into a Regional Facility and to develop the capability to deploy sub-surface instruments in the resulting drill holes, are being provided by Washington Sea Grant. The initial hardware design and actual construction of the drill will be done by Williamson and Associates, Inc., a private marine consulting firm in Seattle. The design parameters include 3-meter penetration of hard rock with diamond drill bits, a core diameter of 35-45 mm from 46-56 mm diameter drill holes, and a drill stand on a tripod base that is 3 meters wide, 4.2 meters high, and weighs 1200 kg in air. Both horizontal and vertical orientation data, along with the necessary drilling parameters, will be telemetered to the surface in real time.

The construction timetable has a series of preliminary shallow water tests (in Puget Sound) scheduled for late summer or fall of 1989, and full scale, deep-ocean (>2000 m) tests on the Washington margin and Gorda Ridge scheduled for early 1990. The rock drill should be available for use by the general scientific community by summer, 1990.

User costs will not be finalized until after the deep water tests are completed, but preliminary estimates are approximately $2000/day for continuous around-the-clock use at sea. With an estimated 4 deployments possible per day, the rock drill costs alone would be less than $200/meter of core. Even with $12,000/day ship-time costs, this would still average less than $1,200/meter of core. Although not a fair comparison, this is somewhat better than the highly successful ODP Leg 118, which, including the full costs of the drilling program for that leg, averaged approximately $12,000/meter of hard rock core.

Development of small over-the-side rock drills has been an illusive goal of marine geologists for the last 2 decades. Recent advances in drilling technology, and improvements in our ability to manipulate remote instrumentation on the seafloor, have dramatically increased our chances of success. In addition, we are now fortunate to have the benefit of the learning experience associated with both the existing small drills that have been tried before, and the twenty years of drilling the seafloor with the DSDP/ODP program. It is time for the marine geological community to build a working rock drill.

Questions or suggestions regarding the basic design parameters, the results of the preliminary tests, or, for the optimistic, inquiries about the scheduling status and availability of the rock drill can be addressed to Paul Johnson, School of Oceanography, University of Washington, Seattle, WA 98195 (206-543-8474: telemail P.JOHNSON.WA).



SEISMIC MAPPING OF THE UPPERMOST IGNEOUS CRUST WITH A DEEP-TOWED EXPLOSIVE SOURCE (DETES)

G.M. Purdy

In marine earth sciences only one technique exists for the absolute ground truthing of structural interpretations based on geophysical observations: drilling. It is of vital importance to learn how to relate seismic observations to drilling results and logging data. This capability is well developed in the sedimentary environment but is extremely limited for igneous rocks. This is an especially serious void in our abilities because it has been repeatedly demonstrated that drilling igneous ocean crust is an agonizingly slow and expensive procedure. Even the most optimistic estimates of the Ocean Drilling Program plans and capabilities over the next ten years do not predict more than 3-5 penetrations into the crust by greater than 0.5-1.0 km. It is, thus, of especial importance that we learn how to make seismic measurements on a scale that can be related to these drilling and logging results so that the few tie points of unequivocally determined structure can be used to extend our knowledge of true geology over lateral scales of many kilometers and more.

It is well-known that in a conventional seismic experiment over young oceanic crust, with low velocities and high gradients near the seafloor, the first arriving energy appearing ahead of the water wave has turned at sub-sea floor depths of 0.5-1 km. All the energy that turned in the uppermost crust is buried in the high amplitude water wave and is, except in a few rare cases, invisible. Thus, in general, in young crust no direct observations of the shallowmost structure is possible even if the seafloor were flat and the layering completely homogeneous. Only when a source is placed close to the seafloor does the energy propagating in the shallowmost crust move ahead of the water wave and become clearly observable. As most of the ocean drilling is restricted to the uppermost 500-1000m, and as in this is the location of both the major known age-related changes in crustal structure (Houtz and Ewing, 1976; Purdy et al., 1985; Purdy, 1986) and the primary volcanic extrusive component of the ocean crust, it is especially critical that we develop methods to map its structure directly and unambiguously. This can best be done using the Woods Hole Oceanographic Institution's Deep Towed Explosive Source (DETES). An early prototype of this system was successfully used on the Mid-Atlantic Ridge in 1985 and obtained the first unequivocal measurements of ~2.5 km/s velocities in the uppermost sections of the young basaltic crust. A new system is currently under construction with funding from NSF and will be used on the Juan de Fuca ridge in June 1989.

The source is towed within 100m of the ocean floor on a conventional 0.68" coaxial cable and is capable of firing, upon command from the research vessel, up to 48 individual 5-10 lb. explosive charges. The explosive used was commercially available Penta-Erythritol-Tetra Nitrate (PETN) that was activated by 14.9 gm m^{-1} Primacord and custom made over-sized Ireco electrical detonators. For safety reasons each detonator is protected by a pressure switch that maintains a short until the source is at depth in excess of approximately 300 m. In addition, a mechanical protector isolates the detonator from the main charge and is only removed by the physical release of the explosive from the source package. These and other safety precautions result in a practical and reliable system that in the coming years will be used to map the details of uppermost igneous crustal structure with a resolution never before possible.

Wednesday Evening Poster Sessions Abstracts

THE PETROLOGY OF SULFIDES AND SULFUR CONTENTS OF OCEANIC GABBROS

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Igneous sulfides in gabbros from the Cayman Rise and ODP/DSDP Holes 735B, 334, and 556 are typical of basaltic melts and are comprised of pyrrhotite, pentlandite and Cu-Fe sulfides. These are recrystallized to low temperature assemblages of chalcopyrite, hexagonal pyrrhotite, troilite, millerite (NiS) and violarite. Many sulfides (especially in the Cayman samples) were replaced by pyrite, marcasite, and Fe-oxides during low-T oxidation. Traces of secondary pyrrhotite, pentlandite, and chalcopyrite occur with talc + magnetite or Mg-Fe amphibole + magnetite replacing olivine and rarely OPX. These assemblages formed during high temperature (600^{o}C) hydration reactions.

Excluding Units 1 and 4, gabbros from Hole 735B average 470 ppm sulfur. The Unit 4 gabbros are highly evolved Fe-Ti gabbros, with correspondingly high primary sulfur contents (1700 ppm). The Unit 1 gabbros are extensively sheared and recrystallized and have very low sulfur contents (80 ppm), indicating loss of crustal sulfur to hydrothermal fluids. Similar effects occur in the Cayman Rise samples, which have lost additional sulfur through low-T oxidation on the seafloor. The lower oceanic crust thus contributes crustal sulfur to hydrothermal fluids through alteration of gabbros, and possibly through degassing of sulfur during crystallization. The lower oceanic crust is an important source of sulfur in seafloor sulfide deposits, and may exert an influence on the geochemistry of sulfur in seawater.

.1.

DRILLING DEEP INTO YOUNG OCEANIC CRUST, HOLE 504B, COSTA RICA RIFT

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Hole 504B is by far the deepest hole yet drilled into the oceanic crust in situ, and it therefore provides the most complete 'ground-truth' now available to test our models of the structure and evolution of the upper oceanic crust. Cored in the eastern equatorial Pacific Ocean in 5.9-m.y.-old crust that formed at the Costa Rica Rift, hole 504B now extends to a total depth of 1562.3 m below seafloor, penetrating 274.5 m of sediments and 1287.8 m of basalts. The site was located where the rapidly accumulating sediments impede active hydrothermal circulation in the crust. As a result, the conductive heat flow approaches the value of about 200 mW/m^2 predicted by plate tectonic theory, and the in situ temperature at the total depth of the hole is about 165 °C.

The igneous section was continuously cored, but recovery was poor, averaging about 20%. The recovered core indicates that this section includes about 575 m of extrusive lavas, underlain by about 200 m of transition into over 500 m of intrusive sheeted dikes; the latter have been sampled in situ only in hole 504B. The igneous section is composed predominantly of magnesium-rich olivine tholeiites with marked depletions in incompatible trace elements. Nearly all of the basalts have been altered to some degree, but the geochemistry of the freshest basalts is remarkably uniform throughout the hole. Successive stages of on-axis and off-axis alteration have produced three depth zones characterized by different assemblages of secondary minerals: (1) the upper 310 m of extrusives, characterized by oxidative 'seafloor weathering,' (2) the lower extrusive section, characterized by smectite and pyrite, and (3) the combined transition zone and sheeted dikes, characterized by greenschist-facies minerals.

A comprehensive suite of logs and downhole measurements generally indicate that the basalt section can be divided on the basis of lithology, alteration, and porosity, into three zones that are analogous to layers '2A', '2B', and '2C' described by marine seismologists on the basis of characteristic seismic velocities. Many of the logs and experiments suggest the presence of a 100- to 200-m-thick layer 2A comprising the uppermost, rubbly pillow lavas, which is the only significantly permeable interval in the entire cored section. Layer 2B in hole 504B apparently corresponds to the lower section of extrusive lavas, in which original porosity is partially sealed as a result of alteration. Nearly all of the logs and experiments showed significant changes in in situ physical properties at about 900-1000 mbsf, within the transition between extrusives and sheeted dikes, indicating that this lithostratigraphic transition corresponds closely to that between seismic layers 2B and 2C, and confirming that layer 2C consists of intrusive sheeted dikes.

A vertical seismic profile conducted during leg 111 indicates that the next major transition deeper than the hole now extends -- that between the sheeted dikes of seismic layer 2C and the gabbros of seismic layer 3, which has never been sampled in situ -- may be within reach of the next drilling expedition to hole 504B. Therefore, despite recent drilling problems deep in the hole, current plans now include revisiting hole 504B for further drilling and experiments when the Ocean Drilling Program returns to the eastern Pacific in 1991. (Oceanic crust, Ocean Drilling Program.)

SUBSOLIDUS ALTERATION AND DEFORMATION OF LAYERED GABBROS: EAST GREENLAND TERTIARY IGNEOUS PROVINCE

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Early Tertiary continental rifting that formed the North Atlantic Ocean basin was associated with extensive igneous and hydrothermal activity. In East Greenland, this activity is recorded in voluminous basaltic lavas and linear, coast parallel, belts of sheeted dikes and layered gabbro intrusions. Excellent exposures due to uplift and glaciation afford an unprecedented opportunity to study the magmatic, structural and hydrothermal histories of these igneous rocks during the initial stages of the opening of the North Atlantic Ocean.

Field and petrographic investigation of the Skaergaard intrusion, the Kruuse Fjord and Kap Edvard Holm complexes, gabbros on the offshore islands of Nordre Aputitêq, Igtutarajik and Patulajivit, and the Miki Fjord macrodike suggest that the style and complexity of hydrothermal alteration in each gabbro complex is closely related to its magmatic and structural history during emplacement and cooling. Characteristic assemblages of hydrothermal minerals are found within all of the intrusions, but each gabbro is characterized by a unique distribution and abundance of mineralized veins, miarolitic cavities and metasomatized gabbros. The earliest hydrothermal alteration consists of calcic amphibole $\pm$ pyroxene-bearing assemblages concentrated in and near veins that are oriented normal or subparallel to the walls of the intrusions. These vein systems were formed between 600–900°C, probably due to cooling and contraction of the intrusion, and were sealed by secondary minerals between ~500–600°C. Mass transfer associated with the hydration and oxidation of olivine contributed to reactions that led to fracture sealing. The combination of high temperature and low water/rock mass ratios led to conditons where the compositions of the early hydrothermal minerals were determined within microscopic domains that vary on a grain size scale. Later assemblages characterized by modally abundant calcic amphiboles, epidote, albite, chlorite or quartz occur in localized areas of the gabbros, formed at temperatures <500–600°C, and are associated with more extensive metasomatic alteration. Orientations of the vein sets that host these later alteration assemblages are closely related to the trends of granophyres, pegmatites or regional dike swarms. Geometric relations of the various vein sets suggest that the permeability in the cooling gabbros changed spatially and temporally in a systematic fashion as older fracture systems and cavities were sealed by secondary minerals and as new fractures formed.

The paleohydrology of hydrothermal groundwaters in the volcanic pile intruded by these gabbros was also complex. Initially fluid flow was controlled by subhorizontal zones of high porosity and permeability (ie. brecciated and vesiculated flow tops and bottoms). This was subsequently modified during the development of the rift system by the infilling of cavities by silicates and carbonates, by emplacement of low permeability dikes and sills, and by extensive fracturing of the volcanics near the gabbro complexes. During the development of the East Greenland continental margin meteoric hydrothermal fluids circulated to depths of >7 km, and the permeability required for this fluid circulation changed dramatically in both magnitude and orientation within and near each of the layered gabbro complexes.

Observations in East Greenland suggest that there is an increase in the complexity of the interrelated processes of multiple intrusion, fracturing, and hydrothermal mineralization from the gabbros located in the coastal mountains to those located in the offshore islands. This is due to a change in style of magmatic and tectonic activity associated with the transition from an incipient continental rift to an oceanic spreading axis.

EXTREMELY RAPID COMPOSITIONAL GRADIENTS IN ULTRAMAFIC CUMULATES FROM THE CY-4 BOREHOLE, TROODOS OPHIOLITE: IMPLICATIONS FOR MAGMA CHAMBER PROCESSES

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(Dept. of Earth Sciences, University of Cambridge, U.K.).

The ultramafic cumulates intersected in the lower third of the CY-4 borehole are characterised by a series of cyclic units which are defined by modal layering on about a three metre scale. Wavelength dispersive electron microprobe data on mineral phases for selected intervals of core sampled at about a one metre spacing reveal cryptic variation at this scale. Particularly striking is the rapid variation in mineral composition with height and the overall coherence in mineral chemistry between coexisting phases within the cyclic units.

The cyclic units suggest a process involving fractional crystallization in an open system magma chamber. Rapid variation in Cr_2O_3 content indicates that a cyclic unit 1.65 m thick formed by crystallization of a magma body of 1.80 m vertical dimension. This thickness is orders of magnitude less than the total thickness of the Troodos cumulate pile; models involving large and well-mixed magma chambers are precluded.

The unexpected overall coherence in vertical profiles of compatible and incompatible elements suggests that, in this cumulate pile, the geochemical consequences of compaction and the concomitant expulsion of an intercumulus melt were limited in extent.

PALEOSTRUCTURES, A MODEL FOR PRIMARY CRUSTAL DEVELOPMENT, BY DR. HUGO BUSER, CONSULTING GEOLOGIST, CH-8882 UNTERTERZEN, SWITZERLAND

Paleostructures are primary crustal elements. Their uniform configuration and persistence may well indicate that their first predisposition has taken place at a period when the crust was still liquid or semiliquid. They therefore may date back into the stellar period of our planet. They have directed or influenced many of the later events, like tectonics, sedimentation, intrusion, extrusion, metamorphism, mineralisation and drainage. Paleostructures can be considered as a primary crustal formation model, before, only in the late proterozoic, plate tectonics with their typical melange series of ophiolites became apparent in crustal processes. They can be determined by their rejuvenation effects on all later events. They may thus be considered as a palimpcest of the primary crustal formation processes.

Origin and modification of paleostructures are shown to be due to the interaction of three main geophysical forces: Geomagnetism, gravitation and rotation. The paleostructural evolution is based upon the assumption that metamorphism, metasomatism, intrusions, extrusions, mineralisation, sedimentation, tectonic activity, in short, the sum af all later alterations, depend upon isostatic readjustment within the paleostructural constitution of the crust. Geomagnetism may have determined the primary pattern of the still liquid crust, at a period of its gradual solidification; gravitation may have caused a differential sinking of the depressions after the original sedimentation had taken place, thus leading to various stages of deformation and invagination-processes with accompanying metamorphism, metasomatism, intrusions and extrusions along zones of maximum sinking. Finally, rotation began to become differentially effective in those areas of invagination, where, as a result of remelting, metasomatism etc., a mass surplus developed: Centrifugal forces, exercising a pull on these areas, led to a regional upwarping, faulting and other structural phenomena, often in connection with hydrothermal and volcanic activities.

Paleostructural investigation therefore has to be carried out in basement and sedimentary areas. Paleostructures were determined by detailed facies analysis in the Jura Mts. (Eurasian margin shelf sediments) in Switzerland, by tectonic studies in the Alps (Thetis orogenic belt) and in Nigeria and adjacent countries in a comprehensive study, where 13 culminations and depressions and an anticlinorium (Northern Nigerian anticlinorium) were determined (West African craton; Cretaceous-Tertiary sedimentary basins along the Atlantic coast from Angola to Westafrica and in the interior, influence on drainage system in Westafrica).

It should be noted that paleostructural investigations are necessarely uncomplete due to the limitation of data. It is proposed that paleostructural research should be carried out on a global scale. A paleostructural global model is presented. It may be of interest also for the understanding of planetary crustal features.

Table 1: Generalized cross-sections of Nigeria and Cameroons, with interpretation of paleostructural evolution

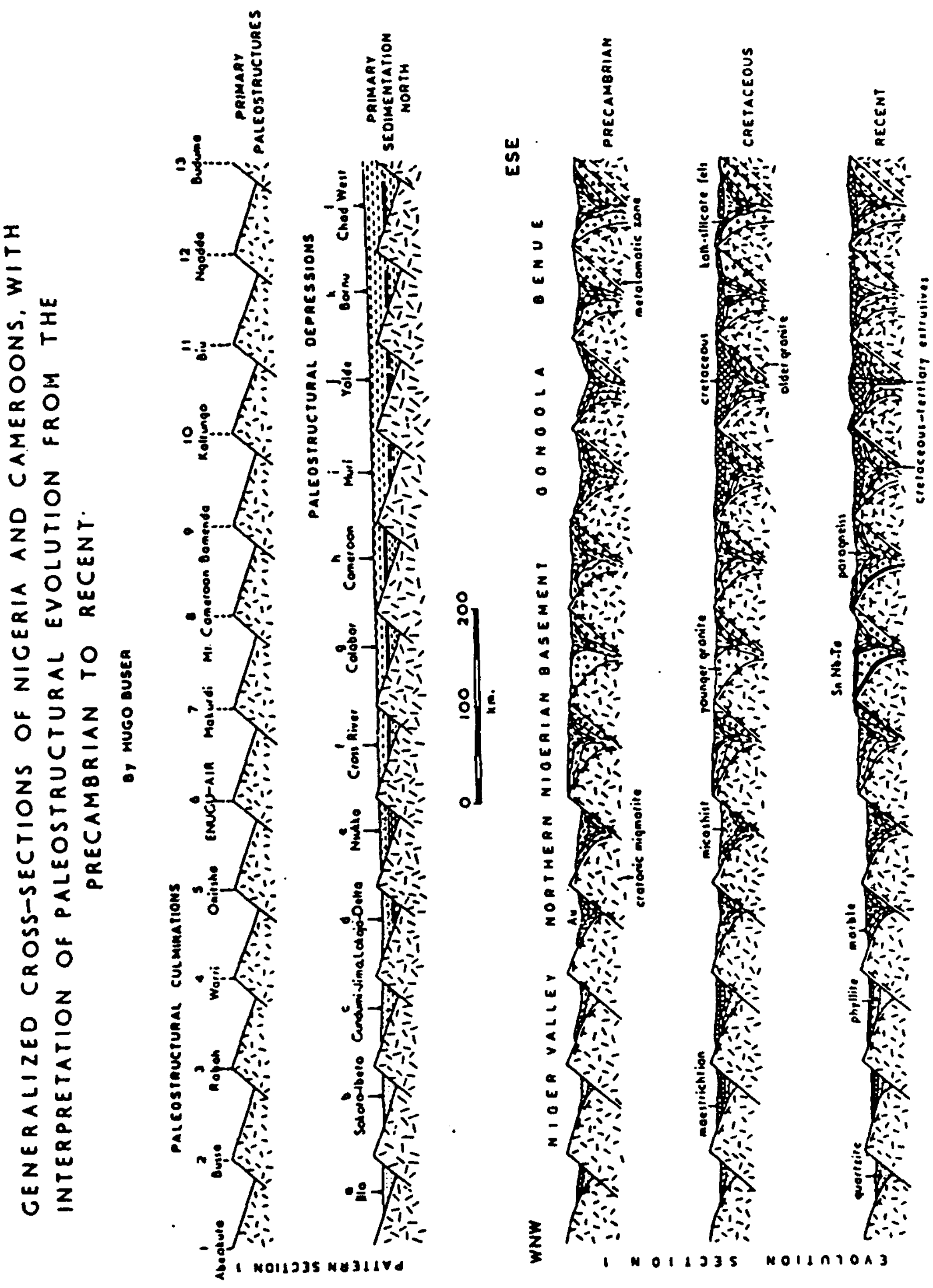
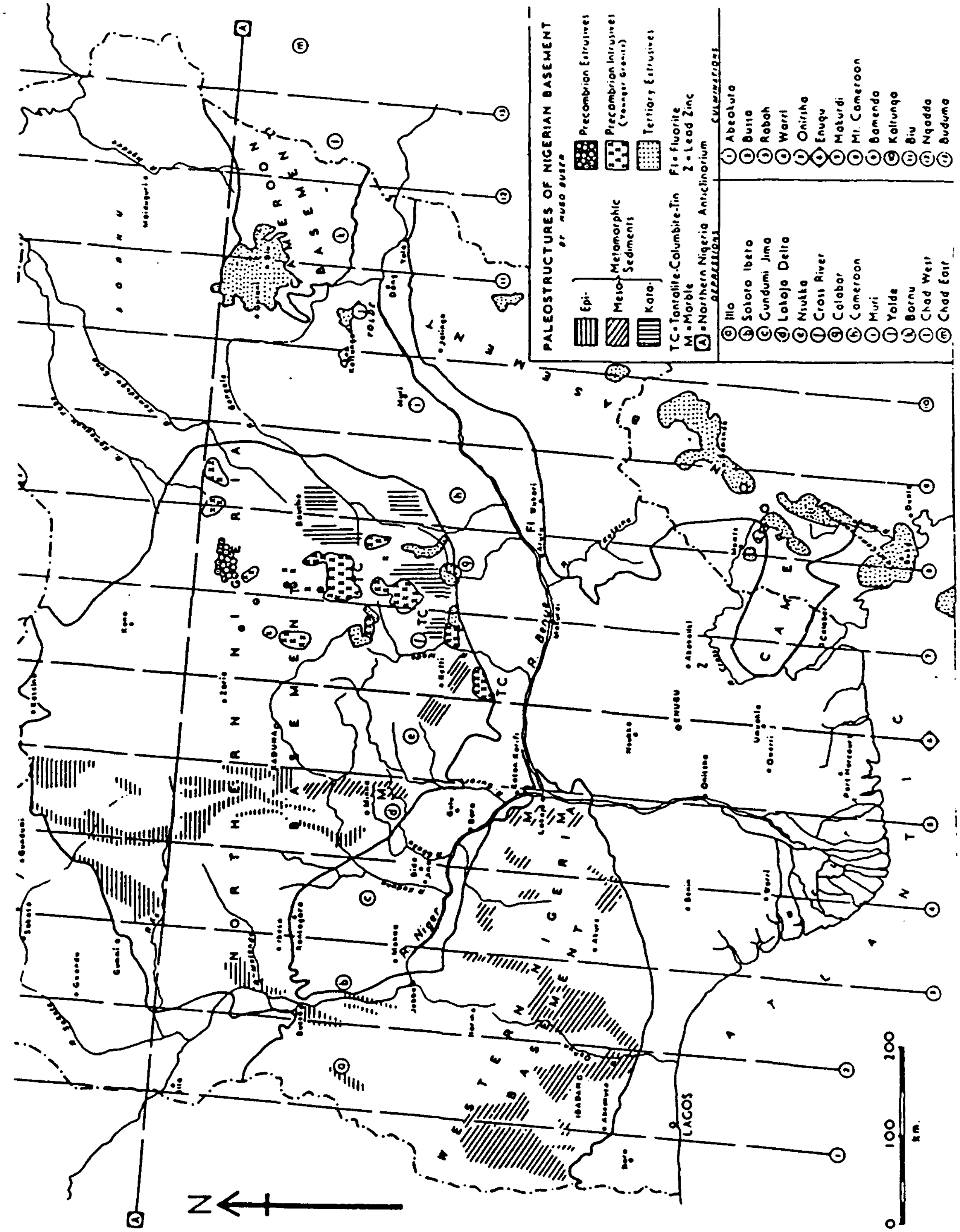


Table 2: Paleostructures of Nigerian basement



MAPPING THE SEISMIC STRUCTURE OF THE UPPER OCEANIC CRUST: IMPLICATIONS FROM DSDP SITE 504B, PANAMA BASIN

J.A. Collins, T.M. Brocher, G.M. Purdy

We investigate the seismic structure of the upper oceanic crust by comparing both reflection and refraction data collected at Deep Sea Drilling Project (DSDP) Site 504B to the results of downhole logging. Extensive processing of the multichannel seismic reflection data, designed to remove high-amplitude side-scattered arrivals, revealed no conclusive evidence for laterally coherent reflection events generated within the upper 1-2 km of the crust. This observation was initially surprising because drilling shows a well-defined change in physical properties at depths within the basement of about 0.5-0.6 km, corresponding to the transition from volcanic rocks to dikes. To better understand the lack of reflectivity from the volcanic/dike boundary at Hole 504B, we calculated synthetic reflection seismograms for a series of velocity-depth profiles constructed from the logged physical properties. Vertical-incidence synthetic seismograms suggest that the volcanic/dike boundary at Hole 504B has a relatively low effective seismic impedance; in these seismograms, reflections from the modeled geological boundary are obscured by source reverberation and sediment-column multiple reflections. The low impedance contrasts within the upper crust at Hole 504B clearly contrasts with those areas where high-amplitude shallow reflections have been observed. The contrasting reflection responses, nonetheless, do not necessarily imply significant differences in the geological structure. The reflection events observed in other areas may be generated at lithological/porosity transitions similar to that samples at Hole 504B, the differences in reflection response may be primarily controlled by the thickness of the transition zone. Synthetic seismograms calculated for wide-angles of offset and observed wide-angle data acquired at Hole 504B indicate that the volcanic/dike boundary is readily identified in such data.

HOW FAR TO MOHO AT 504B?

J.A. Collins, G.M. Purdy, T.M. Brocher

We present an analysis of wide-angle reflection/refraction data collected in the immediate vicinity of Deep Sea Drilling Project Hole 504B, currently the deepest drillhole (1.288 km sub-basement) into oceanic igneous crust. The data were acquired with a tuned airgun array and fixed-gain sonobuoy receivers, and consist of four intersecting profiles shot along three different azimuths. Near-normal-incidence, multichannel seismic (MCS) reflection data were acquired simultaneously.

Iterative forward modeling of travel time and amplitude features common to these four wide-angle reflection/refraction profiles shows that, in comparison to typical oceanic velocity-depth profiles, the velocity structure at Site 504B is unusual in having high velocity gradients at mid crust, a low-velocity zone in the lower crust, and a crustal thickness of only 5 km. Identification of the high velocity gradients at mid crust is prompted by the observation of P-wave amplitude focusing at ranges of 16-19 km on all four profiles. The thickness and mean velocity of the low-velocity zone are jointly constrained by the travel times and amplitudes of well-defined PmP arrivals, and by the 1.4-1.5 s crustal travel time to a Moho reflection event observed on the MCS data. The lid of the low-velocity zone is apparently gradational in character because near-normal-incidence reflections are not observed at the appropriate travel time.

Our preferred model may be considered as a perturbation about typical oceanic velocity-depth models; contrasting viewpoints stress either the 'high-velocity layer' at sub-basement depth of 2.1-3.1 km or the low-velocity layer in the lower crust. A plausible explanation for the high-velocity layer invokes a layer of gabbro with a mean olivine concentration 24-27% greater than that of surrounding rocks. The absolute mean olivine concentration of this layer need be no greater than 13%. With regard to the origin of the low-velocity layer, one possible explanation invokes serpentization of the lower gabbroic crust. A 14-17% increase in the relative amount of serpentine in the lower crust is sufficient to lower P- and S-wave velocities by the required amount.

No conclusions can be made as to which of the above explanations, if either, best explains the unusual velocity structure at Site 504B. Further drilling at 504B could resolve these arguments, however, Hole 504B is an ideal location to drill through the oceanic crust into the upper mantle because the crustal thickness at the site is 1-2 km thinner than typically reported values. At the time of writing, the total sub-basement penetration of 1.288 km is ~25% of the expected crustal thickness. Although the drilling rates attained in the diabase dike sequence have been low, less than 8 m/day (ODP Science Operator Report, 1987), it is likely that rates could increase significantly when the expected gabbroic sequence is reached. At ODP Site 735 on the Southwestern Indian Ridge, ~500 m of gabbro were drilled at an average rate of 30 m/day (ODP Science Operator Report, 1988). In addition, the average core recovery rate was 87%. Assuming that the crust below the bottom of Hole 504B consists of gabbro, and that this high drilling rate could be achieved, the upper mantle could be reached in ~4 months of continuous drilling.

PETROLOGICAL AND GEOCHEMICAL PROBLEMS OF THE DEEP OCEANIC CRUST AND OCEANIC MAGMA CHAMBERS: EVIDENCE FROM OPHIOLITES AND BASIC LAYERED INTRUSIONS

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One of the principal objectives of drilling the oceanic lower crust and upper mantle will certainly be to understand the magmatic processes involved in the formation of these rocks. One of the most important first-order observations is the presence or absence of cumulate ultramafic units. In order to evaluate the importance of cumulate ultramafic rocks in MORB evolution, however, the thicknesses of these units must be well constrained and complete penetration through the petrologic Moho is necessary. Holes that fail to penetrate the entire section of cumulates will not resolve some of the most important questions such as the time-integrated parental liquid composition, variability in the compositions of mantle-derived liquids, and the pressure of formation of basal cumulates.

Studies of cumulate rocks from basic layered intrusions, ophiolites, and MOR spreading centers suggest that the chemical effects that solidified interstitial liquids have on the composition of cumulate or residual crystals need to be carefully documented in order to evaluate magmatic processes. For adcumulate rocks, however, these effects are generally small and would not substantially influence the interpretations. The chemical effects of subsolidus exchange, which are often major and cannot be neglected, also should be documented.

The compositional variations of liquids as they enter crustal magma chambers and the fractionation and mixing parameters involved in the formation of cumulates can be evaluated by detailed, layer-by-layer studies of basal cumulates using both electron microprobe and ion probe data. Results from studies of this type in ophiolites and basic layered intrusions (e.g., Wilson, 1982; Browning, 1984; Komor et al., 1985; Ross and Elthon, 1988) indicate that magmatic replenishments are common and that the volume of liquid undergoing fractionation is relatively small. From the study of sections of cumulate ultramafic rocks, the question of whether magma chambers homogenize compositionally diverse mantle-derived liquids and make them appear to be more uniform or whether existing differences are magnified by magma fractionation processes may be addressed.

Indicators of in situ fracture permeability in oceanic layer 3

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Results of an extensive suite of logging and core measurements acquired along the Atlantis II fracture zone at ODP Site 735 are the first continuously cored and in situ data sets in oceanic gabbroes available for direct comparison. Owing to the nearly constant matrix porosity and borehole size throughout the 500 m interval, detection of changes from mafic gabbro to Fe-Ti oxide-rich compositions and the distribution of fractures is possible from the logging data alone. Compositional changes were verified by core XRF analysis and enabled inversion of the logs for litholgic variations versus depth. Considerable fracture permeability in the upper interval of the hole was indicated by high measured flow rates during drill-stem packer tests, a negative temperature log gradient, and low sonic velocities and amplitudes coinciding with fractures observed in digital televiewer data.

These in situ indicators of fracture permeability in oceanic layer 3 clearly delineate the hydrogeological structure of Hole 735B. Although fine-scale fractures and hydroxyl-bearing alteration minerals are observed in the upper section of the hole, we conclude that high-permeabilities occur primarily as a result of a few isolated, open fractures at about 100, 120, 150, and 290 mbsf which are indicated by high porosity and low velocity and semblance values. The probable direction of the maximum horizontal compressive stress is indicated by the E-W dip orientation of observed conjugate fracture sets, which is perpendicular to the N-S strike of the Atlantis II fracture zone. This suggests that N-S tectonic plate motion near Site 735 does not dominate the regional stress field. The highly permeable fracture system in these low-porosity layer 3 rocks is probably a result of growth faulting during uplift of the walls of the Atlantis II fracture zone.

Oceanic Faults and Shear Zones in the Josephine Ophiolite

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The Josephine ophiolite is a large, complete 162±1 Ma ophiolite exposed in northwestern California and southwestern Oregon. The ophiolite and overlying sediments were thrust >100 km eastward *beneath* western North America, and a coeval magmatic arc complex was thrust beneath the ophiolite. The basal thrust of the ophiolite consists of a sole of antigorite mylonite underlain by amphibolite and gneissic amphibolite mylonite. Ar/Ar and Pb/U ages on the amphibolites and syntectonic plutons indicate that movement on both the basal and roof thrusts was completed by 149±1 Ma (Harper et al., in prep.).

A suprasubduction zone setting for ophiolite generation is indicated by the presence of a coeval volcano-plutonic arc complex in the underlying thrust sheet, tuffaceous cherts and volcanic-rich graywackes overlying the ophiolite, and trace-element chemistry of lavas and dikes. Well-organized spreading is indicated by the presence of a regionally extensive, thick (>1 km) sheeted-dike complex having consistent dike orientations. The orientation of spreading centers in the Josephine basin, inferred from the orientation of sheeted dikes, was east-northeast (Fig. 1a). This orientation is approximately normal to regional trends in the Klamath Mountains and Sierra Nevada and suggests a spreading geometry where short spreading segments are separated by long arc-parallel transforms, similar to the modern Andaman Sea. The Josephine ophiolite probably formed by spreading along the northern extension of the Mojave-Sonora megashear, an intra-arc wrench fault active during Late Jurassic oblique subduction.

The Josephine ophiolite is well suited for the study of oceanic crustal and upper-mantle structures because of the following: (1) well-exposed upper-mantle peridotite covers >800 km^2; (2) water-polished exposures are present in deep canyons which allow detailed structural study; (3) the ophiolite is repeated by folding and faulting which allows geometric relationships between bedding, lava flows, dikes, igneous layering, upper mantle foliations, and oceanic faults to be determined for several homoclinal sections; (4) pelagic rocks which grade upward into turbidites conformably overlie the ophiolite and provide a paleohorizontal datum.

The entire crustal sequence of the Josephine ophiolite is tilted southward ≥50° as indicated by the orientation of sheeted dikes and igneous layering relative to bedding in conformably overlying sediments. Tilting is inferred to have occurred at the ridge axis because uppermost lava flows are parallel to bedding in overlying pelagic rocks, hydrothermal alteration occurs along sheared dike margins, and late subvertical dikes locally cut tilted dikes (Fig. 2). In addition, preliminary data indicate progressive steepening of the dip of lava flows with depth, consistent with growth faulting at the ridge axis. The concept of growth faulting is important for morphologic studies of modern mid-ocean ridges because tilting at the ridge axis can be obscured by later lava flows.

The thickness of the crustal sequence as measured from the top of the pillow lavas to the base of the ultramafic cumulates is only ~3 km. The thin crust appears to be the result of tectonic extension. Modeling of tilting by multiple episodes of rotational faulting suggests that crustal thinning may have been >100% to account for the >50° tilting of the crustal sequence (Norrell and Harper, 1988). The large-scale tilting and inferred attenuation of the *entire* crustal sequence at the spreading axis suggests that there were episodes of tectonic (amagmatic) extension in the absence of a crustal magma chamber (Harper, 1988). This conclusion is further supported by the widespread presence of very primitive lavas within the lower pillow lavas; these lavas could not have been erupted if a crustal magma chamber were present because they would have been mixed into the chamber. In addition, two massive sulfide deposits, which are overlain by up to 5 m of mudstone, occur in one stratigraphic sequence (Turner-Albright deposit) and indicate episodic venting of hot smoker fluids onto the seafloor. The inferred alternation of magmatic and amagmatic extension indicates a relatively low magma supply, consistent with the Josephine ophiolite having formed at a short spreading center bounded by long transforms (cold edge effect).

The ophiolite has undergone several episodes of faulting during and after emplacement. Nevertheless, it is often possible to identify oceanic faults using a combination of the following: (1) crosscutting relationships; (2) temperatures of deformation determined from microstructures, mineral assemblages, and oxygen isotopes; (3) alteration along faults due to subseafloor hydrothermal metamorphism; (4) and geochronology. A number of oceanic faults and shear zones have been documented using these criteria.

A regionally extensive, originally subhorizontal shear zone having an average thickness of ~200 m occurs within the upper mantle harzburgite, up to 1 km beneath the base of the crustal sequence. The shear zone and consists of unusual serpentinite mylonites having a stretching lineation approximately normal to the strike of sheeted dikes in the overlying crustal sequence (Norrell et al., 1989). The temperature of deformation of the serpentinite mylonites is constrained to be ~500°C from microstructures, the local presence of deformed amphibolites, and oxygen isotope geothermometry. Many of the mylonites contain strongly polygonized, and sometimes elongated olivine grains and aggregates within a matrix of highly strained antigorite, indicating that deformation occurred at progressively lower temperatures ranging from >~750°C (lower limit of olivine plasticity) to approximately 500°C. The decrease in deformation temperatures and hydration may have resulted from the influx of hydrothermal fluids. The large thickness of highly strained mylonites implies hundreds, and more likely 1000's, of meters of displacement along this shear zone. This large inferred displacement, the ridge-normal lineation, presence of deformed mafic intrusions, and the originally subhorizontal orientation strongly suggest that this shear zone represents an oceanic detachment fault. Furthermore, the sense-of-shear in the mylonites is down-to-the-south, consistent with the southward tilting of the crustal sequence (Fig. 1a). Natural remnant magnetization (NRM) of the serpentinite mylonites have intensities of 4.2-5.5 A/m; these high values suggest that serpentinite mylonites may be a significant source for oceanic magnetic stripes. Preliminary measurements of NRM intensities in the crustal sequence are low except for moderate intensities (~0.2-0.5 A/m) in amphibolite-facies basal sheeted dikes and high-level gabbros which contain secondary magnetite.

An originally steeply dipping, wide (~475 m) shear zone occurs beneath the serpentinite mylonite detachment in the southern part of the Josephine ophiolite (Fig. 1b, Lookout shear zone). This shear zone consists primarily of peridotite mylonites, suggesting formation at primarily high temperatures (>~750°C). As the shear zone is approached, mantle flow foliations in the surrounding harzburgite bend into parallelism to the shear zone boundaries, indicating that mantle flow was occurring during displacment across the shear zone. Alteration of orthopyroxene to talc is ubiquitous within and adjacent to the shear zone, and suggests that subseafloor hydrothermal fluids penetrated the shear zone. The Lookout shear zone is subparallel to the spreading axis as inferred from the orientation of variably tilted sheeted dikes (Fig. 1b). The orientation and sense-of-shear is consistent with it being a deep-level, plastic extension of a large ridge-parallel fault; however, the large displacement (>2 km) implied by this shear zone is unlike modern mid-ocean ridge faults, except perhaps at the inside corner of ridge-transform intersections.

Oceanic faults in the *crustal* sequence of the Josephine ophiolite can be documented by using features formed during subseafloor metamorphism such as silicification, epidotization, and cross-cutting veins. The following sequence has been established at an excellent exposure of the basal sheeted-dike complex (Fig. 2): (1) intrusion of sheeted dikes and pervasive amphibolite-facies subseafloor metamorphism, followed by localized retrograde greenschist-facies alteration; (2) 50° tilting of the sheeted dikes, small-scale faulting along dike margins, and steeply dipping normal faulting; (3) formation of abundant prehnite±epidote or quartz veins and breccias in the sheeted dikes and along small faults; and (4) intrusion of a thick Fe-Ti dike along a steeply dipping fault which cuts both tilted sheeted dikes and prehnite veins. These relationships indicate that tilting occurred directly on-axis as hydrothermal circulation became progressively cooler, fracture porosity (vein density) increased, and rare (along axis?) dike injection occurred.

Several large oceanic faults have also been identified in the crustal sequence:

(1) A fault zone in pillow lavas which is locally metasomatized to epidosite and grades upward into a semi-massive sulfide deposit. Epidosites and silicification have been interpreted by previous mineralogic and isotopic studies to form from discharging hydrothermal fluids similar to hot smokers.

(2) A low-angle fault zone >3 m thick between the sheeted dike complex and pillow lavas is present in the "type section" of the sheeted dike complex. The fault zone consists largely of silicified fault breccia containing chalcopyrite and sphalerite. Pillow lavas above the fault are largely silicified, whereas sheeted dikes below the fault contain abundant epidosite stringers. The transition from epidosites in the sheeted dike complex to silicified rocks of the fault zone and pillow lavas has been interpreted to be the result of cooling of hot (~350°C) discharging hydrothermal fluids at the ridge axis.

(3) A >5 m-thick fault zone within the lower sheeted-dike complex consists of silicified fault breccia. Displacement of 100's of meters across the fault is suggested by the width of the fault zone and juxtaposition of sheeted dikes having screens (septa of country rock) of pillow lava and gabbro, respectively.

(4) Massive sulfide deposits at the Turner-Albright deposit are situated along the north side side of a fault zone which is subparallel to the strike of underlying sheeted dikes. Debris flow breccias, thick massive ponded lavas, and intercalated mudstones are unusual features of the volcanic section at this locality. These features suggest that hot smoker fluids vented along a ridge-parallel oceanic fault zone along the edge of a back-tilted basin (Kuhns and Baitis, 1987; Zierenberg, et al., 1988).

Subtle features in the lower sheeted dike complex that indicate large-scale displacements (≤1 km) at the spreading axis prior to the final episode of dike injection include (1) the local presence of screens of pillow lava, and (2) screens of diabase talus breccia. In the upper sheeted-dike complex, gabbro screens occur locally; these screens appear to have formed below the sheeted dike complex because of their coarse grain size and presence of relict amphibolite-facies assemblages.

The Josephine ophiolite generally has a simple, mappable pseudostratigraphy, even though the crustal sequence apparently underwent periods of very large amounts of extension resulting in rotational faulting above an oceanic detachment. Documentation of oceanic faults and shear zones has required detailed mapping, structural and microstructural observations, and a thorough study of subseafloor hydrothermal metamorphism.

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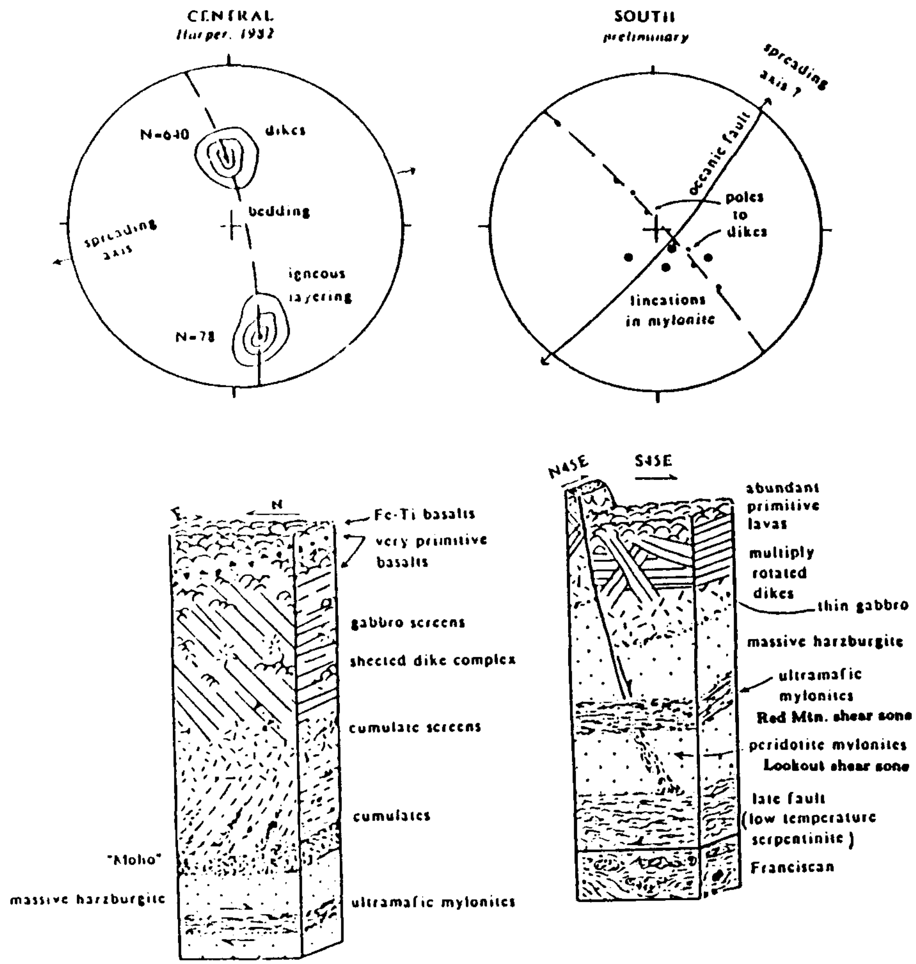

FIGURE 1. a. Orientation of structures in the Josephine ophiolite after correction for folding. b. Orientation of structures in the SW portion of the ophiolite. This area is unusual because of a very thin crustal sequence, variable orientation of sheeted dikes, and a steeply dipping shear zone beneath the upper mantle detachment.

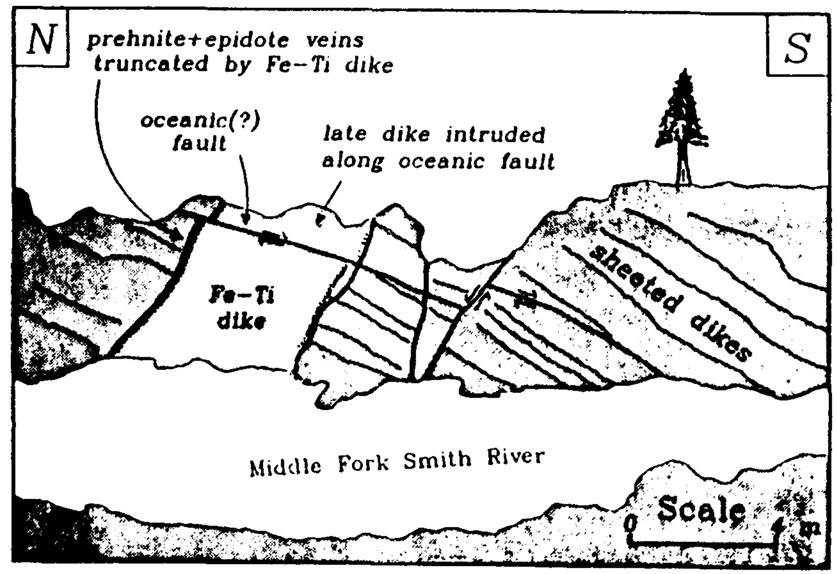

FIGURE 2. Exposure of the basal sheeted-dike complex along the Smith River, NW California. Because this exposure is located in the hinge of a gently plunging syncline, structures are orientated essentially the same as when they were beneath the spreading axis. The dip of the sheeted dikes reflects tilting at the spreading axis. The sketch shows the location of several probable oceanic faults, some of which are the locus of abundant prehnite veins. A late highly fractionated dike was intruded along one of these faults and much of its margins were subsequently sheared and veined with prehnite.

SOLEA GRABEN - TROODOS OPHIOLITE: TECTONIC THINNING AT A RIDGE - TRANSFORM FAULT INTERSECTION.

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Structural and geophysical data from the Solea graben in the north-central region of the Troodos Ophiolite confirm a primary spreading origin of the graben. Dikes in the western portion of the graben are rotated on listric faults that sole into a graben wide detachment, near the dike-gabbro contact. Most of the extension has occurred in this 10km wide flank of the graben where dike dips are consistently less than 50°, always toward the graben axis. Thickness of the sheeted dike section on the western side may be as little as 500m, much less than the 2km thickness generally assumed for the dike section in most of the complex. The eastern side of the graben reflects a complex history of multiple magmatic intrusions of gabbro and massive diabase as well as block rotations about both vertical and horizontal axes. The diabase section is also relatively thin on the eastern side.

The first-order geometric characteristics of the Solea graben, its location just north of the ultramafic outcrop on Mt. Olympus and the Arakapas Fault Zone, are consistent with the interpretation that this fragment of ancient oceanic lithosphere represents a fossil ridge-transform intersection (RTI). The extensional structures in the Solea graben, including steep normal faults, grabens, rotated dikes and low-angle detachments are also observed near the Kane Fracture Zone - Mid-Atlantic Ridge RTI. The plutonic rock outcrop centered at Mt. Olympus, lies at the intersection of the extensional structures of the Solea graben and the transform fault structures of the Arakapas Fault Zone. It may represent an exposure of crust and upper mantle that formed beneath an RTI nodal basin. Mid-ocean ridge spreading center RTI's show many of the same geometrical relationships as those exposed in the Troodos Ophiolite at the same scale, implying a similar origin.

Igneous Textures and Primary Mineralogy of Gabbros from Site 735B

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The shipboard scientific party divided the core into 6 stratigraphic units based on lithology, down-hole logs (e.g. magnetic susceptibility), bulk-rock geochemistry, and mineral chemistry. Unit 1 consists of metagabbro with porphyroclastic to mylonitic textures, the protolith being a gabbronorite with approximately 10% orthopyroxene. The principal rock type in Unit 2 is an olivine-bearing gabbro or olivine gabbro. Thin layers and intervals rich in Fe-Ti oxides are common and often exhibit porphyroclastic to mylonitic textures. Basaltic dikes intrude Unit 2 in two locations. Unit 3 is similar to Unit 2 but is marked by the development of strong igneous lamination with dips varying from 60° at the top to 5° at the bottom. The principal rock type in Unit 4 is ilmenite gabbro with 5% to 25% Fe-Ti oxides. Olivines and pyroxenes are uniformly iron-rich and plagioclases are uniformly sodic. A pronounced igneous lamination is sub-horizontal. Trondhjemitic veins (up to 4 cm) occur near the bottom of the unit. Unit 5 consists of homogeneous olivine gabbro with uniform mineral compositions. The principal rock type in Unit 6 is olivine gabbro with frequent intercalations of troctolite and ilmenite gabbro. Stratigraphic spikes in magnetic susceptibility and in mineral compositions reflect sharp contacts between gabbro types, magnetic susceptibility correlating directly with abundance of Fe-Ti oxides.

Textures and grain sizes in Hole 735B are extremely variable. The gabbros can be divided into three main textural types: 1) granular gabbros with tabular or prismatic plagioclase, subhedral clinopyroxene, and anhedral to subdhedral olivine; 2) oikocrystic gabbros with clinopyroxene crystals reaching 10 cm in length; and 3) equigranular microgabbros, which are distinctly finer grained (0.5-1.5 mm) than the main gabbro units. Intervals in the core exhibit modal, phase, and size-graded layering. Modal layers, most commonly defined by a concentration of olivine, tend to be 1 to 5 cm thick and are spaced at irregular intervals from 5 cm to 50 cm apart. Size-graded units are marked by an upward fining in crystal sizes from 10-20 mm to 1-5 mm. Magmatic foliation is well-developed from 150-300 m below the seafloor with a dip that decreases progressively from 60° to nearly horizontal.

The gabbros exhibit a continuous range in mineral compositions, olivine varying from Fo_{83} to Fo_{30}, that is comparable to what is observed in layered intrusions like the Bushveld and Skaergaard. Associated with the change in mineral compositions is a systematic change in the cmumulus mineral assemblage, from olivine (Fo_{83}) + plagioclase (An_{74}) + clinopyroxene to plagioclase (An_{50}) + pigeonite (now inverted) + clinopyroxene $\pm$ ilmenite to olivine ($Fo_{<60}$) + plagioclase ($An_{<45}$) + clinopyroxene + ilmenite. The appearance of ilmenite as a cumulus phase is also manifested by a drop in TiO_2 in clinopyroxenes. This is the first documentation of such a mineral paragenesis in oceanic rocks, though the assemblages have been predicted in one-atmosphere experiments.

Many of the gabbros cored at Hole 735B contain abundant iron-titanium oxides (ilmenite + magnetite) and intimately associated sulfides (pyrite, pyrrhotite and chalcopyrite, among others). Modal abundances of 3-10% are common and some unusual intervals contain 20-50% of these opaque minerals. These occurrences correspond generally to rocks which are extremely fractionated, but there is also clear evidence that secondary mobilization has produced some zones of concentrated oxides and sulfides in the most highly deformed gabbros. The origin of frequent laminae of ilmenite gabbro within the olivine gabbro is unclear. The ilmenite gabbro may represent either a post-solidification injection of evolved melt or a late-stage liquid segregated from the main cumulate body, possibily by filter pressing or localized pooling of dense immiscible melts.

The proportion of liquid trapped and crystallized between cumulus grains has been estimated from the bulk-rock geochemical data using the mass balance approach of Meyer et al. (1988). Based on these calculations most of the gabbros at Site 735 are mesocumulates with residual porosities between 7% and 25% (avg. = 11%). A few of the more magnesian gabbros are adcumulates with less than 7% trapped liquid. Such low residual porosities indicate slow cooling rates typical of at least moderate-sized intrusions. The inferred range in liquid compositions exceeds the known range for Southwest Indian Ridge basalts.

Digitization of an electron microprobe map of one gabbro which depicts cumulus cores and post-cumulus overgrowths shows that 45% of the plagioclase and 65% of the clinopyroxene represent post-cumulus overgrowths. These are much higher values than the 10-20% trapped liquid estimates derived from the mass-balance calculations. The image analysis and elemental maps appear to show the total amount of post-cumulus growth while the chemical data provide an estimate of the amount of liquid actually trapped in the rock, that is, the amount of intercumulus liquid at the time when the cumulate pile became effectively impermeable.

THE AGENT OF HIGH-TEMPERATURE, HYDROTHERMAL ALTERATION IN THE OCEANIC CRUST: MODIFIED SEAWATER OR EXSOLVED MAGMATIC WATER ?

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The existence of mid-ocean ridge magmas having greater than 0.5% Cl and 1% H_2O means that some of the high-temperature alteration observed in deeper crustal rocks could be due to exsolved magmatic volatiles, and **not** to the interaction of oceanic crust with modified seawater.

Cl increases from ≈40 ppm in primitive MORB, to >1000 ppm in FeTi basalts, to >5000 ppm in rhyodacites from fast and medium-spreading ridges. The extreme variations require the input of Cl from a source that is external to the crystallizing magma (chamber). Assimilation of large amounts of altered crust or much smaller amounts of Cl-rich brines or minerals during fractional crystallization (AFC) could account for the variations. The most likely mechanism for generating the Cl variations in magmas is deep penetration of seawater and alteration of the lower crust, followed by its incorporation into the crystallizing magma. Paradoxically, much of the alteration observed in gabbros may be related to Cl-rich volatiles exsolved from these magmas. In other words, some of the Cl in altered oceanic gabbros may have been cycled through a magma chamber before being incorporated into the oceanic crust and after being a component of seawater.

Curiously, while MORB suites from fast- and medium-spreading ridges show similar and large amounts of Cl-overenrichment, MORBs from slow-spreading ridges show very little Cl overenrichment. Highly evolved MORBs are also rare from slow-spreading ridges. The correspondence of Cl-enriched magmas and highly evolved magmas suggests that the formation of highly evolved magmas may be related to assimilation of colder, altered crust.

Studies of oceanic gabbros have assumed that all Cl-rich alteration is caused by (modified) seawater. Because of the limited accessibility of the lower crust at medium- and fast-spreading ridges, studies of oceanic gabbros have concentrated on slow-spreading ridges. Drilling could provide access to the lower oceanic crust of a medium- or fast-spreading ridge, in order to determine if there are significant differences in hydrothermal circulation and alteration with slow-spreading ridges. Permeability measurements in a deep hole at a fast- or a slow-spreading ridge could provide constraints on the ability of seawater to circulate in the deep ocean crust. It is possible that deep penetration and direct alteration occurs in relatively restricted zones while exsolved magmatic volatiles account for dispersed alteration in less permeable zones.

FINE-SCALE VARIATIONS IN MINERAL COMPOSITIONS OF MASSIVE DUNITES FROM BLOW ME DOWN MTN., BAY OF ISLANDS OPHIOLITE

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At this time, detailed knowledge of deeper levels of oceanic crust, particularly in a well-constrained stratigraphic context, is available only from ophiolite studies. In this work, we present data on mineral compositions from a fine-scale traverse through a section of massive basal dunites from Blow Me Down Mountain. This traverse comes from the deepest levels of the thick massive dunites, just above the residual harzburgite section. Eighty-four samples, covering twenty meters of section, have been analyzed by electron microprobe for olivine and chrome-spinel compositions. These data are consistent with a cumulate origin for the massive dunite section. These samples are adcumulates containing greater than 90 modal per cent olivine and serpentine, with accessory chrome-spinel and occasionally minor clinopyroxene and sulfides. No orthopyroxene has been observed in our samples from the massive dunites.

Olivine compositions in this suite range from forsterite 89.4 to 91.7, with NiO from 0.26 to 0.45 wt. %, CaO from 0.05 to 0.29 %. Olivine compositions in the residual harzburgite section on Blow Me Down Mtn. are Fo 90.5 to 91.4, NiO from 0.45 to 0.62 %, CaO < 0.05 %. These data support an origin by crystal fractionation from very primitive to primary magmas for the dunite section. When viewed as a function of stratigraphic height, mineral compositions in these dunites display repeated reversals toward more refractory values. This feature is caused by replenishments of un-fractionated magma. The frequent repetition of these reversals over brief stratigraphic intervals suggests that these small magma inputs undergo initial stages of fractionation prior to mixing with more voluminous evolved magma resident in the chamber. Wider recognition of the prevalence of these fine-scale magmatic variations in cumulate rocks from ophiolites and basic-layered intrusions is essential for a better understanding of fractionation processes in mafic magma chambers.

Chrome-spinel compositions in these dunites are Cr-numbers: 20.2 to 61.3, Mg-numbers: 77.4 to 51.5, TiO_2 is 0.05 to 0.45 %. These spinels are similar to those observed in abyssal peridotites in terms of their Mg- and Cr-numbers, however their titanium abundances are notably higher. TiO_2 in spinels of abyssal spinel-peridotites is commonly less than 0.10.

Hydrothermal Systems in Continental Layered Intrusions and Implications for the Lower Oceanic Crust

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Direct observations of hydrothermal fluids venting from hot springs at mid-ocean ridge spreading centers have led to major revisions in models of heat and mass transfer between the oceans and the oceanic crust. It is becoming increasingly clear that intense hydrothermal activity is not restricted to the upper oceanic crust. An important goal of future oceanographic research is to assess the nature and global significance of hydrothermal processes in the lower oceanic crust. Drill core from the Atlantis II transform on the southwest Indian Ridge (ODP Leg 118, Hole 735b; 32°43.40', 57°16.00') provides the most complete record of the lower oceanic crust recovered from the ocean basins to date. Preliminary studies of the drill core (Stakes et al., 1988; Kempton et al., 1988; Vanko, 1989) indicate that there are significant similarities between hydrothermally altered gabbros from ocean layer 3 and those from continental layered mafic intrusions. Insights into hydrothermal alteration of the lower oceanic crust can be gained from studies of continental layered intrusions that are well exposed and have not been appreciably affected by regional metamorphism or tectonic deformation.

The most instructive and complete set of observations of gabbro-hosted hydrothermal systems have been made on the Bushveld Complex (Schiffries, 1985; Schiffies and Skinner, 1987; Schiffries and Rye, 1988) and the Skaergaard intrusion (Taylor and Forester, 1979; Norton et al., 1984; Bird et al., 1986; 1988). Despite differences in age, size, bulk composition and tectonic setting between the Bushveld Complex and the Skaergaard intrusion, there are important similarities between the hydrothermal systems that modified their primary features. Both intrusions are crosscut by extensive networks of hydrothermal veins that formed as a consequence of fracture-controlled fluid flow. Many outcrops are characterized by vein frequencies that range from 0.2 to 5 m^{-1}, and local areas have vein frequencies that exceed 50 m^{-1} (vein frequency is reported as total vein length per unit area and has units of m^{-1}). Hydrothermal veins commonly occur along steeply dipping sets of conjugate fractures that formed at an early stage in the cooling history of each intrusion.

Fluid-rock interactions in the Bushveld Complex (Schiffries and Skinner, 1987) and the Skaergaard intrusion (Bird et al., 1986; 1988) occurred over a broad range of physical and chemical conditions, producing a wide variety of hydrothermal veins. The secondary mineral assemblages associated with the veins are similiar to those found in mafic igneous rocks that were subjected to metamorphism under conditions ranging from upper amphibolite facies to sub-greenschist facies. Geothermometers generally yield temperatures of 500 to 900°C for veins with amphibolite facies assemblages (calcic amphibole $\pm$ pyroxene $\pm$ oxides $\pm$ plagioclase), and 300 to 600°C for veins with greenschist facies assemblages (actinolite $\pm$ clinopyroxene $\pm$ albite $\pm$ epidote $\pm$ sphene). It appears that gabbroic intrusions are commonly affected by fluid-rock interactions at temperatures considerably higher than the maximum temperatures attained by hydrothermal fluids at mid-ocean ridge hot springs.

Studies of both the Bushveld Complex and the Skaergaard intrusion have established that the field and petrographic manifestations of high temperature (> 500°C) fluid-rock interations may be extremely subtle. For example, oxygen isotopic data indicate that many ostensibly fresh rocks from the Skaergaard intrusion have undergone extensive isotopic exchange with hydrothermal fluids (Taylor and Forester, 1979). It should be emphasized, however, that fluid-rock interactions do not necessarily produce large shifts in $\delta^{18}O$ values. Certain high temperature veins in the Bushveld Complex have $\delta^{18}O$ values that are nearly indistinguishable from those of fresh samples that retain their magmatic isotopic signature (Schiffries and Rye, 1988). These observations indicate that conventional approaches for monitoring hydrothermal activity in other geologic environments may not be reliable for monitoring high temperature fluid-rock interactions in gabbroic intrusions.

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Fluid-Rock Interactions and the Metamorphic History of Layer Three of the S.W. Indian Ridge: ODP Site 735

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The 435 m of almost continuous igneous and metamorphic rock that was recovered from ODP Site 735B is remarkable for its heterogeneity. Horizons of deformed rocks are found at all depths in the core, however the ductile deformation is concentrated in three intervals (0-70 mbsf; 250 to 273 mbsf; 405 to 500 mbsf) with moderately dipping foliations (15^{o} to 40^{o})' down-dip lineations and a dominantly normal shear sense. The intensity of the ductile deformation is maximum in cores 5 and 6 (21 to 26 m), and in core 56 (271 m). The core can thus be divided into three fault bounded sections: an upper section of foliated metagabbros down to cores 5 and 6, an intermediate section down to core 56, and a lower section below core 56. The upper half of the core contains horizons of plastic deformation that vary from foliated gabbros to mylonites. These strongly deformed zones separate sections of isotropic gabbro that show variable cataclastic deformation and are replaced by amphibolite grade assemblages. This complex of deformed gabbro that comprises the upper part of the core is crosscut by high angle veins of amphibole (magnesio-hornblende to ferroan pargasitic hornblende with up to 1.4% Cl) with lesser quantities of plagioclase and hematite. Fluid inclusions in secondary plagioclase and hornblende have homogenization temperatures from 150^{o} to $350^{o}C$, and those in quartz from rare granophyre are 340^{o}. There are two-phase and restricted occurrences of three-phase fluid inclusions indicating local generation of saline brines. We suggest that the vein network results from dynamic cracking and seawater penetration that may be characteristic of ocean crust forming near transform intersections. This upper section of core is predictably depleted in oxygen isotopes to compositions as low as 4 per mil reflecting this high temperature alteration and abundant seawater. Midway through the core, zones of hydrothermal breccias appear more frequently than high strain horizons. These are zones of cataclastic deformation and progressively lower temperature assemblages (epidote, chlorite, sphene, diopside, smectite, carbonate). They may represent horizons of permeability deep within the crust. In the lower half of the core, remarkably fresh olivine gabbro is interlayered

with the brecciated horizons and with horizons of renewed deformation. In the intermediate and lower section, the original magmatic relationships between the successive lithological units are often preserved. Fluid inclusions in the primary phases preserve magmatic compositions, most notably a methane component. Alteration (presence of hydrous replacement assemblages) is strictly associated with cracks, shears or breccia zones. The replacement assemblages include sodic plagioclase (An5-40), clinozoisite (Ps10-20), pargasite, phlogopite, sphene, anthophyllite, cummingtonite, talc and magnesio-hornblende. These are frquently observed in static coronitic replacements. Gabbros away from these cracks retain their magmatic oxygen isotopic composition, precluding significant pervasive seawater circulation at high temperatures. Late oxidative alteration is observed in the upper 10's of meters of the cores as well as associated with the breccia horizons down core. In the oxidized zones, olivine and orthopyroxene are replaced by carbonate-hematite-smectite pseudomorphs, resulting from low temperature oxidative alteration. The gabbro fragments from the breccias are stained bright red from Fe-oxide. A strontium isotopic composition of a large carbonate-smectite vein showed that it was precipitated from normal seawater . This confirms that the breccia horizons were zones of continued permeability. It is not clear whether the low temperature seawater alterature ensued after the several kilometers of uplift necessary for the exposure of the layer 3 gabbros or whether they are evidence of the penetration of cold seawater to several kilometers depth along major faults as fluid pathways.

A Vertical Seismic Profile in Layer 3, Atlantis II Fracture Zone, Southwest Indian Ridge

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During Ocean Drilling Program Leg 118, the SEDCO/BP 471 drilled at site 735C into bare rock in 720m of water atop the east wall of the Atlantis II Fracture Zone, Southwest Indian Ridge. Drilling penetrated 500.7 mbsf and recovered 435 of gabbro and metagabbro. We obtained a vertical seismic profile using a 3-component seismometer clamped at 22 depths in the borehole. A 1000 cu. in airgun and a 400 cu in water gun were fired alternately at each receiver depth. A weak reflector at approxmately 1 km below seafloor was detected in the airgun data. Preliminary processing indicates a relatively uniform P wave velocity of 6.4 to 6.5 km/s. This velocity, characteristic of ocean layer 3, supports the ophiolite model of ocean crust. The up-going wavefield, when separated by ω-k velocity filtering, shows coherent reflectons. These reflections correlate with the principal downhole changes in lithology.

THE TROODOS OPHIOLITE AND IMPLICATIONS FOR THE LOWER OCEANIC CRUST

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The Troodos ophiolite of Cyprus represents a remnant of Mesozoic Neotethyan oceanic crust. The presence of axial grabens and normal faults parallel to the grabens within the sheeted dike complex and the extrusive sequence are reminiscent of oceanic spreading centers. Complex intrusive and tectonic contact relationships between the sheeted dike complex and the underlying plutonic complex indicate multiple and episodic intrusions of magma and spatial variation in volcanic and tectonic activities. Generally north-south trending sheeted dikes and normal faults in the eastern part of the ophiolite curve to an east-west orientation towards the Arakapas transform fault zone in the south suggesting transmission of transform-related shear stresses into the spreading center domain. These relations suggest the origin of the ophiolite near a transform fault-spreading center intersection. Regional reconstructions suggest that the ophiolite may have formed in a marginal basin over a south-dipping subduction zone which evolved as a complex system of spreading centers and transform faults separating a series of microcontinents. A detailed petrographic study of the ICRDG drill core (CY4), which sampled 2300 meters of a nearly complete core through the sheeted dike and plutonic complexes, suggests that the ophiolite is composed of at least two distinct magmatic suites. An early high-TiO_2 basaltic suite constitutes upper gabbros, sheeted dikes, and andesitic to rhyodacitic lower extrusives. A late low-TiO_2 basaltic andesite suite constitutes the lower ultramafic to gabbroic cumulates and upper extrusives. The gabbros related to the early suite show complex cryptic variation with three reversals to more primitive mineral compositions (1/200 m), while the lower cumulates show only one reversal (1/1000 m). The reversals are gradual and are interpreted to reflect magma chamber replenishments. Only the upper gabbro sequence is structurally and geochemically related to the sheeted dike complex and crustal spreading. The late magmatic suite can be related to the second-stage melting which mainly underplated the ophiolite *sensu stricto*. Several tectonic and geochemical features suggest that the spreading processes that generated the ophiolite were different from those documented in modern oceanic basins. However, the lack of spreading related steady-state magma chambers, the relatively thin crust (~5 km), and the possibility for underplating by second-stage melt are interesting possibilities for, at least, an early stage of a major ocean basin development.

TEMPERATURE LOGGING IN HOLE 735B : PREMIMINARY MODELING

By

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Discussion and Summary

The unusual temperature gradient determined for Hole 735B may be closely approximated by some relatively simple steady-state thermal conduction models. Very high conductivity regions (a factor of 100 greater than regional values) are used to simulate zones which may be permeable to sea water percolation. First, the negative temperature gradient in the upper part of the hole apparently can be modeled only by placing a high conducting layer beneath a normally conducting one; it cannot be produced with a uniformly high conducting layer, even with a negative ocean temperature gradient, because the sloping sea floor boundaries of the ridge are apparently too distant to counteract the effects of the heat flow from below implied by the measured deeper temperature gradient. However, a more complex conductivity structure could probably approximate the temperature structure more exactly.

Relatively high permeability (conductivity) extends to depths of nearly 400 m below sea floor (bsf) in both models. The models lose resolution with increasing depth as a result of the unequal grid spacing in the finite-element models, such that the depth uncertainty at 400 m is of the order of 50 to 75 m. The standard logging at this site shows that units with moderate porosity (15 to 20%) persists to depths of 400 mbsf, and the temperature logs themselves show anomalies which may result from permeable zones to depths over 250 mbsf. The packer experiments give relatively high permeability ($\sim 10^{-14}\ m^2$) to about 300 mbsf, also with relatively poor depth resolution.

The preliminary results of this study of the temperature logs suggests that sufficient permeability which allows sea water advection may exist to depths of at least 300 mbsf and perhaps greater at site 735. The geothermal heat flux appears relatively modest, $\sim 30\ mW\ m^{-2}$, for sea floor formed only 10-12 Ma, a result which is not too surprising in view of the anomalous topographic situation at the site.

DSDP HOLE 418A AS A SITE FOR DEEP CRUSTAL DRILLING

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As an alternative to drilling tectonically exposed portions of the lower oceanic crust and mantle, DSDP Hole 418A offers an excellent opportunity to drill through the layer 2-3 transition and into gabbros of layer 3. The hole already penetrates 544m subbasement into the layer 2B-2C transition from pillows to dikes. Site 418 is located in old (110 m.y.), cold Atlantic crust, where thermal stresses which caused extensive problems during deep drilling of younger crust (e.g., 6 m.y. old Site 504B) are absent. Projected temperatures at depths of 1 and 2 km at Site 418 are only 43 and 67°C, respectively, in contrast to the current 160°C at 1 km depth in Hole 504B. Hole 418A is clear of drilling obstructions, and previous drilling penetration and recovery rates were excellent. The site has been extensively surveyed and abundant data from DSDP Legs 51-53 to Site 418 and the immediate area already exist. Deep drilling at Site 418 will allow comparison of oceanic crust formed at fast (Hole 504B) and slow (418A) spreading ridges, and allow evaluation of the effects of steady-state versus intermittent magma chambers on the oceanic crust. In particular, models for crustal structure, igneous geochemical processes, hydrothermal circulation and alteration, and the state of stress in the crust can be tested. Deep drilling of an entire crustal section, such as at Site 418, is necessary to penetration through the layer 2-3 transition and understand the nature of this boundary.

Intracrustal Reflectors in Mesozoic-Aged Crust in the Western North Atlantic: A Target for Deep Crustal Drilling

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Multichannel seismic data obtained in the western North Atlantic during the 1979 North Atlantic Transect experiment (NAT Working Group, 1985; McCarthy et al. 1988), and more recently in a two-ship MCS experiment which we carried out in 1987, reveal a remarkably complex acoustic character to this ~150 Ma old oceanic crust. The upper crust is in some places characterized by a gently undulating, sub-horizontal reflector ~0.5-1.0 sec (~1-3 km) below the top of oceanic basement that can be followed laterally for distances of at least several kilometers. The lower crust is associated with steeply inclined (30-40^o) planar reflectors dipping toward the ridge axis. In a few instances these events can be traced into the upper crust and through the entire crustal section. Isochron-parallel reflection profiles are characterized by strong, planar reflectors dipping at angles of 15-30^o toward the fracture zone. In some cases these events clearly cut through the entire crustal section. The Moho in this area has a variable character, ranging where it is seen from a simple reflector to a complex band of events ~.4 sec wide with variable amplitude and continuity.

The geological significance of these events, some of which have been imaged for the first time, is controversial and will likely be debated for years to come. Ultimately drilling, together with related borehole logging and downhole experiments, will be required to "ground-truth" the origin of these geophysical-defined horizons and determine their relationship to the geological structure and tectonic evolution of oceanic crust. The use of boreholes to define the nature of seismic reflectors that can be mapped widely and cost-effectively using geophysical techniques is a common and powerful technique in the study of sedimentary stratigraphy both on land in the ocean basins. With our improved ability to image the internal structure of the oceanic crust, this same approach should be an important objective of deep drilling in the oceanic crust.

Because of the quality of the seismic images available from Mesozoic-aged crust in the western North Atlantic, this area should be considered a prime target for crustal drilling. Some seismic horizons exist at relatively shallow crustal depths (1-3 km) that are potentially reachable with present drilling technology. Other drilling targets in the lower crust and upper mantle will require advanced drilling systems capable of total crustal penetration in water depths in excess of 6 km.

Pop Up Tectonics and the Formation of Transverse Ridges: a Tectonic Model for the Evolution of a Half Kilometer Section of Layer 3 Drilled Near the Atlantis II Fracture Zone

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ODP Leg 118 recovered 435 m of foliated and massive gabbro from a 500 m hole in a wave cut platform at 700 m water depth on the crest of the transverse ridge forming the eastern transform wall of the Atlantis II transform. Simple plate tectonic reconstruction shows these gabbros formed 11 ma beneath the valley of the ancestral SW Indian Ridge some 15 to 18 km from the ridge-transform intersection and represent the first coherent section of Layer 3 drilled in the ocean crust. Assuming simple subsidence of the platform along the age-depth curve due to lithospheric cooling puts the platform at sea-level when this section of crust was at or near the ridge transform intersection. As with the emplacement of mantle peridotite at St. Paul's Rocks in the Atlantic, the emplacement of such deep plutonic rocks to shallow depth without an overlying shallow crustal section is one of the major conundrums of marine tectonics.

We see a possible explanation for this phenomenon, however, in the asymmetric spreading of the crustal section and the contrasting topography on opposing walls of the median valley at many ridge-transform intersections and the transform and non-transform walls of the inactive fracture zone valley at slow-slipping fracture zones. Like many such transform faults, the transform and non-transform walls of the Atlantis II FZ are strikingly different. The transform walls are great transverse ridges as shoal as 700 m. Along these ridges largely peridotite, gabbro and greenstone have been dredged. In contrast the non-transform walls, formed by the ridge-parallel valleys and ridges of the SW Indian Ridge rift mountains, gently slope downward to meet the adjoining wall of the fracture zone, and rarely shoal more than 3500 m. The transform walls are morphologically a series of horsts, while the non-transform walls seems to be old uplifted and back-tilted rift valley floor with many small seamounts and volcanic features from which only weathered pillow lavas have been dredged. Thus, transform tectonics has dismembered the crust near the ridge-transform intersections, with the shallow levels preferentially spreading away from the transform, exposing deep crustal sections along the transverse ridge.

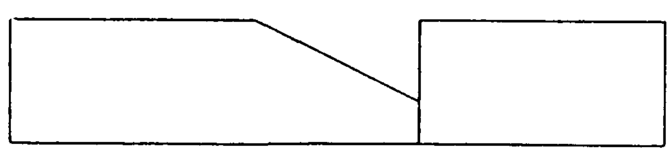
Roughly 30% of the gabbros drilled on the transverse ridge show gneissic to mylonitic plastic deformation concentrated at 3 intervals. The average dip of the foliation rotates from 30° to 20° down hole consistent with stacked listric normal faults. Extensive amphibolite facies alteration is localized in the deformed zones, though numerous amphibolite facies hydrothermal veins cross-cut the massive gabbros as well. The vein orientations have a strong maximum orthogonal to the foliations, and have a corresponding rotation from 60° to 70° down hole. Little retrograde greenschist alteration was found. Apparently cracking during on-going inelastic brittle-ductile zone deformation beneath the rift valley permitted hydrothermal circulation which terminated abruptly in the amphibolite facies. This is likely due to the formation of new master faults within the rift valley locally terminating active extension of older crust and beginning uplift of a major block of rift valley floor into the adjacent rift mountains.

The situation at the N-S trending Atlantis II Fracture Zone seems nearly identical to that at the E-W trending Kane Fracture Zone in the north Atlantic. At the Kane Fracture Zone detailed photo-geologic studies and submersible dives at the eastern ridge-transform intersection have shown that the western wall of the nodal basin and the median valley adjacent to the transform consist largely of metabasalt and gabbro exposed on low-angle normal faults dipping towards the floor of the nodal basin. These faults are offset by later high-angle normal faults. The opposite eastern wall of the median valley, which is uplifted to form the non-transform wall of the fracture zone, consists only of pillow basalt flows uplifted on high-angle normal faults similar to the second generation of normal faults on the western wall of the rift valley. These observations, and those at the Atlantis II Fracture Zone suggest that the shallow levels of the ocean crust forming at the ridge-transform intersection are welded to the older plate and spread asymmetrically away from the transform. This results in the emplacement of plutonic rocks to the sea floor in the transform domain. Such a process explains the formation of nodal basins on the transform side of the neovolcanic zone at ridge-transform intersections.

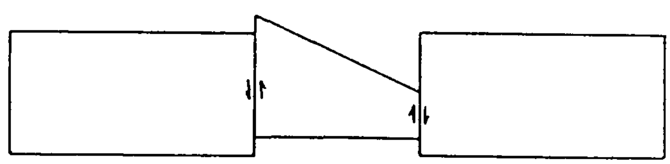
There are a number of processes at ridge-transform intersections which may produce a negative mass anomaly there. These include the thinning of the ocean crust far from volcanic centers located at the mid-points of the adjacent ridge segments, viscous head-loss of the mantle upwelling beneath the ridge axis against the old cold lithosphere at the ridge-transform intersection, as well as the preferential spreading of the upper levels of the crust away from the transform described above. The floor of the nodal basin in the transforms, for example is typically 2-3 km deeper than crust of the same age spreading away from the transform. In addition, the overall architecture of ridge segments is such that the neovolcanic zone plunges 1 to 2 km from the mid-point of a ridge segment to the floor of a fracture zone. This large anomaly, shown in the simple block model below (A), could be compensated for by simple block uplift resulting in the formation of a transverse ridge (B). Alternatively, the crust may simply bow upwards by simple flexure - ridge parallel topography in the rift mountains at many ridges does in fact appear to do this locally as it approaches the transverse ridge at some fracture zones (C). Another possibility is that the amount of uplift of the floor of the transform might be small due to the relatively high viscosity and thicker lithosphere present there due to the transform edge effect. Back faulting may also occur, rather than simple up-bowing, particularly where the transform is undergoing extension due to recent changes in the pole of rotation (D). This appears to be the case at the Atlantis II Fracture Zone in the region of Site 735B.

The advantage of this model over previous ones explaining transverse ridges, is that it does not require a large low-density serpentine diapir to provide the driving force for uplift. This has become a major problem as no evidence for such a low density body is seen in the gravity data collected over transverse ridges, which rather appear to have a normal or higher than crustal density. Rather it suggests that due to the elastic strength of the lithosphere near ridge transform intersections at slow spreading ridges, any negative mass anomaly created locally by transform-edge effects at the ridge-transform intersection will be compensated regionally, rather than locally, causing the local uplift of the crust and shallow mantle adjacent to the transform.

A.



B.



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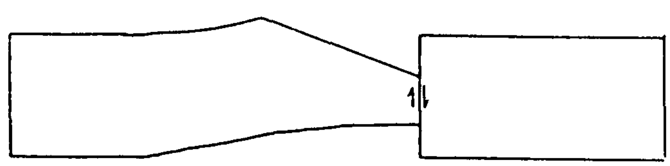
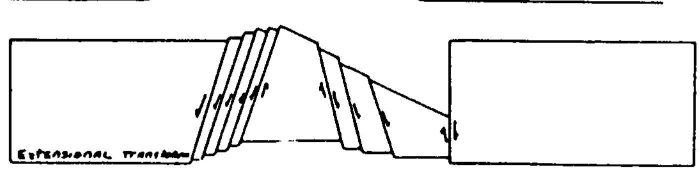


D.



It now appears that transverse ridges provide a unique opportunity to drill and sample the deep ocean crust directly. In particular, wave cut platforms on such ridges provide unique opportunities to drill within major tectonic blocks in regions relatively unaffected by the late stage tectonics associated with unroofing and emplacement of these blocks. Besides the wave cut platform at the Atlantis II F.Z., the possibility exists that we can drill directly into the mantle on a similar platform at the Vema F.Z. (E. Bonatti pers. comm.). Rift valley walls at ridge-transform intersections, often expose plutonic rocks, as at the eastern intersection of the Kane F.Z. Drilling at such locations, however, provides more an opportunity to study the fault mechanisms associated with tectonic uplift of major blocks into the transverse ridges, than an opportunity to study undisrupted sections of layer 3 or the shallow mantle. Gabbroic rocks dredged from the rift valley wall of the MAR adjacent to the Kane Transform, for example, show extensive greenschist facies alteration, which is nearly lacking in the 735B cores, which were drilled from within a tectonic block in the transverse ridge. The extensive greenschist facies alteration in the Kane gabbros is interpreted as due to late stage hydrothermal circulation during uplift on the bounding fault at the rift valley wall. It would be misleading to assume that such alteration is representative for oceanic gabbros in layer 3.

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HYDROTHERMAL DISCHARGE ZONES IN THE OMAN OPHIOLITE AND THE GEOMETRY OF HYDROTHERMAL CIRCULATION AT OCEANIC SPREADING CENTERS

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The area in the Oman ophiolite containing the volcanic-hosted Bayda and Aarja massive sulfide deposits exposes a cross-section of ocean crust, revealing the fossil zones of upwelling that fed these 95 Ma seafloor deposits. The fossil discharge zones are elongate areas of mineralization and alteration characterized by numerous small (meters to tens of meters), linear, discontinuous gossans. The gossans result from oxidation of hydrothermal pyrite replacing primary igneous phases and filling voids and fractures in the altered host rocks. The two deposits have separate discharge zones which appear to be sub seafloor (and along strike) extensions of their stockworks. The Bayda zone extends through the volcanics into the upper sheeted dike complex, and is interpreted as having formed on the ridge crest above an axial magma chamber. The Aarja zone terminates against a plagiogranite pluton intruding into the lower volcanic section, and is thought to have formed after Bayda in an off-axis environment. Structural, stratigraphic, and compositional characteristics of the Bayda and Aarja massive sulfide bodies are consistent with this interpretation. The geometry of the discharge zones suggests that in both cases upflow occurred in broad zones (at least 400 m wide) that were elongated along strike (i.e., parallel to the spreading axis). We suggest that hydrothermal convection at ridge crests differs fundamentally from ridge flank circulation due to differences in the thermal and permeability structure of the crust in the two settings. We propose a two-layer model for circulation at ridge crests, with shallow, moderate-to-low temperature convection (at high W/R ratio) in the volcanics coexisting with deeper, high-temperature convection (at low W/R ratio) through the sheeted dikes. In our proposed model, circulation through the sheeted dikes is mainly along-strike, due to anisotropic permeability in the dike section and along-axis variability in the thermal and permeability structure of spreading centers. Discharge from the dike complex occurs above zones of recent intrusion or on the upwelling limbs of axis-parallel convection cells.

Drilling Escarpments on the Mid-Atlantic Ridge: Composite Sections Through the Oceanic Crust ?

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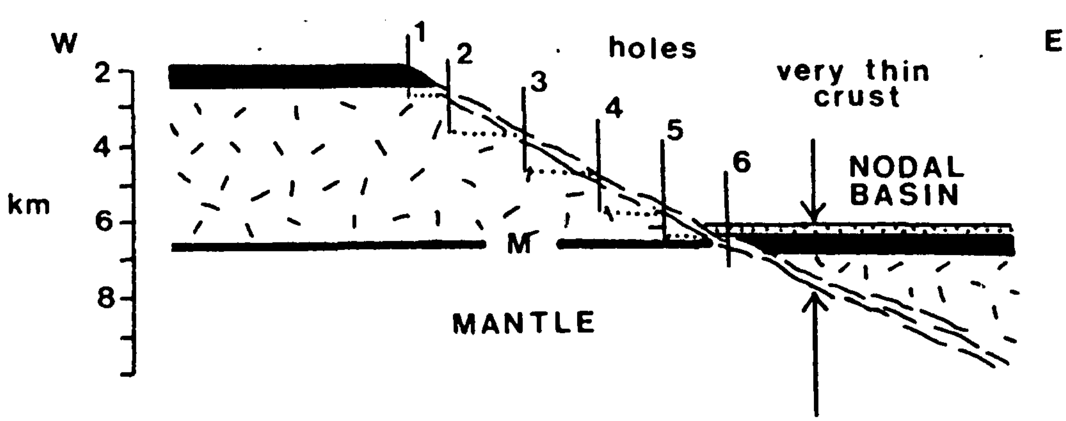
Recent submersible studies of the median valley walls of the Mid-Atlantic Ridge (MAR) show that extensive exposures of plutonic rocks occur on some of the major faults that bound the median valley. Some of these occur near fracture zones where the seismic crustal thickness is somewhat less than average values while other exposures are tens of kilometers away from known fracture zones. Given the present drilling technology, these escarpments provide a means of constructing a composite section through the oceanic crust with a series of closely spaced holes of itermediate to shallow depth. Naturally, such areas may not represent typical oceanic crust in terms of the local tectonic setting, however such crust may be more or less normal in its overall composition and internal structure.

A good prospect for such drilling is the western wall of the the MAR median valley near the Kane Transform. In this area there is more than 4000m of vertical relief between the floor of the ridge-transform intersection nodal basin (6000m) and the top of the wall (<2000m). The overall slope is about 30 degrees and in detail is made up of numerous steep escarpments and intervening terraces. The middle and lower parts of the wall are basically a dip-slope of variably deformed rocks defining a major low-angle detachment fault. Above 2500m highly fractured basaltic rocks crop out but the rest of the slope (2500-6000m) is underlain by gabbroic rocks. This exposure of plutonic rocks is at least 10km wide (EW) and is most simply interpreted as a undeformed footwall beneath the detachment fault. This fault zone extends beneath the nodal basin and seismic delay-time studies of Cormier et al. (1984) indicate that the crust beneath the nodal basin is <1km thick. The Moho beneath the nodal basin may therefore lie in the footwall of the low-angle fault zone. A series of 6 1km-deep holes along an EW transect from the top of the wall to the nodal basin could be used to construct a composite section through the crust. The same could be accomplished with a larger number of more closely spaced holes.

There are two major limitations of this plan: 1) Such crust will almost certainly not have a typical seismic structure and therefore lithologic correlations with seismic horizons will not be possible. 2) Borehole geophysical properties will not be comparable to normal oceanic crust because the confining pressures will be reduced due to the lack of overlying crustal units. Despite these problems, such sites should be considered as complementary to deep drilling of the full thickness of the crust at a single point.



The Mathematician Failed Rift: Exposures of East Pacific Layer Three for Deep Crustal Drilling.

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Abundant Layer 3 rocks are exposed at the Mathematician Ridge (MR), a failed spreading center in the East Pacific. This topographic feature extends roughly N-S on the Pacific plate at 111°W, extending from about 15° to 20°N. Tectonic reconstructions based on Seabeam bathymetry and magnetic anomalies suggest that (Mammerickx, et al., 1988, JGR 93, 3025-3040): a) the full spreading (half-rate = 45-50mm/yr) between the Pacific and Rivera plates occurred here prior to rift abandonment; b) the propagation of the nascent EPR coupled with the progressive failing of the MR resulted in a clockwise rotation of the MR paleoplate; c) dual spreading occurred on the MR and the EPR (half-rate = 25mm/yr) until complete rift abandoment. Previous work on dredged gabbros, metagabbros and serpentinites shows that the exposures of plutonic rocks on the rift valley walls require from 1-3 km of uplift. Following Harper (1988, Geology, 16, 831-834), we suggest that this uplift was the result of amagmatic crustal extension with back-rotation of fault-bounded slices of oceanic crust. This predominately amagmatic extension occurred during the dual spreading episode at the slower spreading rate, transforming the fast-spreading topography (central horst) into a slow-spreading (central graben) topography. The predominately amagmatic nature of this extension has left gabbroic rocks produced by fast-spreading in the East Pacific exposed at the top of the axial escarpments. Syn- and post-abandonment magmatism were apparently small in volume and chemically distinct from the pre-abandonment gabbroic rocks. Syn-abandonment lavas are primitive in composition and indicate the absence of an axial magma chamber. Post-abandonment lavas comprise alkalic seamounts that may reflect an episode of trans-tensional extension during the rotation of the spreading axes.

The phenomenal drilling results of ODP Leg 118 dramatically illustrated the advantages of drilling into gabbro that has been tectonically unroofed. The MR site is far from any large offset transforms and thus avoids the inherent ambiguity of ridge-transform intersections. The MR provides a deep crustal drilling target into fast-spread East Pacific crust to provide the plutonic complement to ODP Site 504B and the planned EPR sites. Propagating/failed rifts and paleoplates are, in addition, now recognized as important aspects of mid-ocean spreading magmatism and tectonics. The magmatic effects of rift failure are a minor, yet distinguishable component of the MR crustal sequence, so that the impact of rift failure on crustal structure can also be assessed at this proposed site.

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16. Abstract (Limit: 200 words)

This workshop was convened to follow up on the Second Conference on Scientific Ocean Drilling (COSOD II) to devise a specific plan for deep crustal and mantle drilling over the next decade. Since COSOD II, however, there have been several developments which have had major impact on planning for this drilling. These include new and evolving models for volcanic segmentation at ocean ridges, a growing appreciation that faulting and deformation are an integral feature of the ocean crust, and the recent successful drilling during Ocean Drilling Project Leg 118 into a tectonically exposed section of layer 3 at Site 735B at the Atlantis II Fracture Zone in the Indian Ocean.

The community has come to realize that while obtaining complete penetration of the crust at a few sites remains a critical goal for ocean drilling, these will be inadequate to characterize a heterogeneous ocean crust. Thus, in order to evaluate fully crustal composition and structure, crustal drilling must include both an ongoing attempt to attain total crustal penetration, and a major program to drill offset partial sections of the deep layers of the crust and their critical contacts. Accordingly, this workshop has formulated a global strategy for using drilling to systematically study an ocean crust whose composition and structure is laterally variable and changes with spreading rate and tectonic setting.

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